DEVELOPMENT OF A SMART FACTORY PROTOTYPE IN CONTEXT OF INDUSTRY 4.0

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A thesis submitted in
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ABSTRACT

The disruption caused by digitalization and the Internet, the increase in labour costs and the demand for a better work-life balance have led to the emergence of the fourth industrial revolution or also called Industry 4.0. In this work, a smart factory prototype was developed to showcase the application of digitalization, data exchange, Internet of things, system integration and usage of ICT in a manufacturing system, in order to automatically produce a customized product. The smart factory concept was specified by a system model showing the system's elements and its dependencies. A prototype was constructed by retrofitting a modular trainer with Industry 4.0 elements while using currently available components such as RFID, PLC and network components, which was connected to a local area network with an Internet connection. A SCADA software was used as the backbone of the system to interface various devices for monitoring, control, and data exchange to a database. It was also used to build a user interface for local and remote access through the Internet. Evaluations based on the VDMA Industry 4.0 Toolbox were conducted in terms of functionality and Industry 4.0 application level. The prototype managed to increase its Industry 4.0 application level from 0.3 to 2.3 from a maximum level of 4.0 according to the VDMA toolbox. In conclusion, the smart factory prototype that was developed by retrofitting an existing system can be used to showcase the concept of Industry 4.0 to improve understanding on Industry 4.0.

ABSTRAK

Perubahan teknologi akibat digitalisasi dan Internet, peningkatan kos buruh, dan permintaan untuk keseimbangan hidup yang lebih baik, telah membawa kepada pengenalan revolusi perindustrian ke-empat atau Industri 4.0. Dalam penyelidikan ini, sebuah prototaip kilang pintar telah dibangunkan untuk menunjukkan applikasi digitalisasi, pertukaran data, *IoT*, integrasi sistem, dan penggunaan *ICT* untuk menghasilkan produk yang disesuaikan secara automatik. Konsep kilang pintar dizahirkan melalui satu model sistem yang menunjukkan elemen-elemen sistem dan kebergantungannya. Sebuah prototaip telah dibina dengan mengubahsuai beberapa alat latihan modular dengan elemen-elemen Industri 4.0 dan dengan menggunakan komponen sedia ada seperti RFID, PLC, dan komponen rangkaian seterusnya disambungkan ke rangkaian kawasan tempatan dengan sambungan Internet. Perisian SCADA digunakan sebagai tulang belakang sistem untuk menghubungkan pelbagai peranti untuk pemantauan, kawalan, dan pertukaran data ke pangkalan data. Ia juga digunakan untuk membina antara muka pengguna untuk akses setempat dan akses luar melalui Internet. Penilaian menggunakan *VDMA Industry 4.0 Toolbox* telah dijalankan dari segi kebolehfungsiannya dan tahap aplikasi Industri 4.0. Prototaip tersebut telah berjaya meningkatkan tahapnya dari 0.3 ke 2.3 daripada tahap maksimum sebanyak 4.0 mengikut penilaian VDMA. Kesimpulannya, prototaip kilang pintar ini telah dapat dibangunkan dengan mengubahsuai sistem sedia ada dan ia dapat digunakan untuk mempamerkan konsep Industri 4.0 untuk meningkatkan pemahaman berkaitan Industri 4.0.

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LIST OF PUBLICATIONS

1. **SMART FACTORY REFERENCE MODEL FOR TRAINING ON INDUSTRY 4.0**
   5th International Conference on Advances in Mechanical Engineering (ICAME 2017), Ao Nang Villa Resort, Krabi, Thailand, August 16-18, 2017
   Published in Journal of Mechanical Engineering (JMechE), Vol. 16(2) 2019

2. **SPECIFICATION OF PRINCIPLE SOLUTION FOR A SMART FACTORY EXEMPLIFIED BY ACTIVE STRUCTURE**
   2017 IEEE 3rd International Symposium on Robotics and Manufacturing Automation (ROMA), UPM, Serdang, Malaysia, September 19-21, 2017
   Published as proceeding, ISBN: 978-1-5386-2539-2

3. **INDUSTRY 4.0 SMART FACTORY REFERENCE MODEL FOR TVET**
   Conference on Creativity and Innovation in TVET (CCITVET) 2017, ADTEC Taiping, Malaysia, November 2, 2017
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4. **SYSTEMATIC DEVELOPMENT OF SMART FACTORY USING CONSENS**
   4th International Conference on System-Integrated Intelligence (SysInt 2018), Hannover, Germany, June 19- 20, 2018
   Published in Procedia Manufacturing, vol. 24, pp. 278–283, 2018

5. **CONCEPTION OF LOGISTICS MANAGEMENT SYSTEM FOR SMART FACTORY** (as Co-Author)
   Published in International Journal of Engineering and Technology (UAE), vol. 7, no. 4, pp. 126-131, 2018

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	-	Three Dimension
AC	-	Alternating Current
ADS	-	Automation Device Specification
ADTEC	-	Advanced Technology Training Centre
AI	-	Artificial Intelligent
API	-	Application Programming Interface
AR	-	Augmented Reality
ASEAN	-	The Association of Southeast Asian Nations
CAD	-	Computer Aided Manufacturing.
CONSENS	-	Conceptual Design Specification Technique for the Engineering of Complex Systems
CPS	-	Cyber-Physical System
DC	-	Direct Current
DFKI	-	*Deutsches Forschungszentrum für künstliche Intelligenz* - German Research Centre for Artificial Intelligent
DPM	-	Digital Power Meter
ERP	-	Enterprise resource planning
ETP	-	Economic Transformation Program
GDP	-	Gross domestic product
GTAI	-	Germany Trade and Invest
HMI	-	Human Machine Interface
ICT	-	Information and Communication Technology

ID	-	Identification
IEC	-	International Electro-Mechanical Commission
IIS	-	Internet Information Services
IO	-	Input Output
IoS	-	Internet of Services
IoT	-	Internet of Things
IoTDS	-	Internet of Things Data & Services
IP	-	Internet Protocol
IPv4	-	Internet Protocol Version 4
IPv6	-	Internet Protocol Version 6
IT	-	Information Technology
JSON	-	JavaScript Object Notation
LAN	-	Local Area Network
M2M	-	Machine to Machine
MES	-	Manufacturing Executing System
MITI	-	Ministry of International Trade and Industry
MIPS	-	Million Instruction Per Seconds
MPS	-	Modular Production System
MQTT	-	Message Queuing Telemetry Transport
MSSQL	-	Microsoft SQL Server
NKRA	-	National Key Results Area
OPC	-	Open Platform Communication
PC	-	Personal Computer
PLC	-	Programmable Logic Controller
RAMI 4.0	-	Reference Architectural Model *Industrie* 4.0
RFID	-	Radio-Frequency Identification
RMK	-	*Rancangan Malaysia Ke-*

RS 232	-	Recommended Standard 232
RS 485	-	Recommended Standard 485
SAP	-	Systems Applications and Products in Data Processing
SCADA	-	Supervisory Control And Data Acquisition
SFC	-	Sequential Function Chart
SMI	-	Small Medium Industry
SOP	-	Standard Operating Procedure
TCP/IP-	-	Transmission Control Protocol/Internet Protocol
TLS	-	Transport Layer Security
TVET	-	Technical and vocational education training
USB	-	Universal Serial Bus
UTHM	-	*Universiti Tun Hussein Onn Malaysia*
V	-	Volt
VDMA	-	*Verband Deutscher Maschinen- und Anlagenbau* (Mechanical Engineering Industry Association)
VR	-	Virtual Reality
WIP	-	Workpiece in Progress

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CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia is well-known as a manufacturing hub. One of the factors behind this is its cheap labour cost. Cheap labour has always been favourable in comparison to a highly automated system which needs a huge amount of initial investment and skilled workers. Due to this, manufacturers often move their production operation to countries with cheaper labour costs [1,2]. Among the problems that arise is the migration of labours between countries, causing disruption in the receiving countries' labour market and social ecosystem [3]. With the increase of awareness and movement of labour organizations in countries that used to provide cheap labour including Malaysia, the demand for higher wages [1], better working environment and better work-life balance [4] have been increasing, when then increases production cost [5]. Furthermore, governments of countries that used to provide cheap labour including Malaysia has implemented various pro-labour related policies such as minimum wages [1,6] and introduced several stringent labour-related laws. This seemed to affect Malaysia, which used to be a manufacturing hub because of its affordable labour [7]. If the increase of wages is not aligned with the increase in productivity [6], manufacturers will need to move to a country that could provide cheaper labour with more productivity in order to stay competitive [2] such as China [8] or adopt to use automation [1]. This will affect the regional economy especially if multinational companies pull out their investment.

Additionally, the buying habits of consumers are changing rapidly [7,9]. e-commerce is swiftly taking over conventional shopping [10,11]. Online shopping is getting more popular [9,10] as consumers can review the item they want to buy [12], compare prices and purchase them at the click of a mouse. At the same time, the product life cycle is getting shorter [13–17] in which products are constantly updated every now and then and the introduction of new models or versions is becoming faster [18,19]. The idea of mass customization [4,14,20–22] of products is not far away as people nowadays want exclusivity [13]. Other than that, social media today has already become part of our lives and influences many things. Nowadays, a lot of disruption has occurred that is caused by advancement in technologies and new inventions [5,7,14] and all of these are available with an affordable price tag [22–24]. This is also supported by the existence and advancement of information and communication technology (ICT) infrastructures and software development [5] such as the high-speed Internet, large data centres and various intelligent software or applications [23,25].

The current trend of Industry 4.0 could be a way to adapt to the various trend that is currently arising such as trend related to the Internet or as mentioned above and can be a solution to problems such as labour cost, demand for a work-life balance or as mentioned above [5,8,26,27]. The Industry 4.0 trend was initially the German government's initiative to establish Germany as the main provider of advanced manufacturing solutions [4,20,23,28]. Although the term Industry 4.0 was first coined by the Germans, other countries such as Japan, the United States, and China have also been looking into the concept under different names [4,5,17,27,29,30]. Industry 4.0 is commonly associated to the Cyber-Physical System (CPS), Internet of Things (IoT), smart factory, and Internet of Service (IoS) according to [31] in which digitalization, data transfer between systems and the Internet are the focal point [4,5,20, 23,25,32]. Advanced manufacturing and automation are interconnected using ICT [9,26,27,32–34] and linked worldwide through the Internet [4,9,30,32]. The aim is to optimize the whole value chain [33]. It is called Industry 4.0 because it is said to be the fourth revolution [23] in the industry after the introduction of steam power and mechanization in the first revolution, mass production line and electricity in the second revolution and computer and automation in the third revolution [4,20,22,23]. Among its applications are the smart factory, smart and customized products, smart logistics, smart home, office or buildings, smart mobility, and smart energy and environment monitoring or smart grid [4,22,25,32].

Industry 4.0 could be the solution in maintaining Malaysia as a manufacturing hub, thus boosting the regional economy because it depends on highly automated and interconnected systems rather than cheap labour [8]. The role of workers will change to be more technical, dynamic and flexible. This will increase the income per capita and is hoped to provide a better and balanced work to life quality [4,35]. On the other hand, Small and Medium Industries (SMI) could also benefit from this revolution because it will make them more productive [19] and they can reduce their labour cost and increase their profits [20]. Furthermore, SMIs usually do not need a very complex system, which makes it easier to maintain [34]. With Industry 4.0, SMIs could subscribe to many useful services from the cloud, thus saving costs on software and ICT equipment [5,25,29]. This will give more opportunity for SMIs to use ICT in their production [4,29].

Industry 4.0 is currently being defined [9,31,36] and no concrete definition currently exists [2,23,32,37]. Thus, industries, solution providers, academicians, researchers, and policymakers are currently in discussion and are researching on Industry 4.0 [9] to set a clear path, standards and fundamentals for the fourth industrial revolution [22]. Therefore a clear understanding and approach to Industry 4.0 are still lacking [30,31]. One of the challenges is to create awareness and make people understand the benefits of this revolution [30]. Other than that, the investment in new technology will be huge [27,37] and without the economic scale, it would be unworthy [26]. Before this revolution is fully implemented, it is wise to understand this revolution mainly to prepare the future workforce to handle such technology [30,34]. To better understand the concept of Industry 4.0, a prototype is needed to show its concept, how it works, how it can be implemented, and to investigate and proof whether the concept can be implemented and is viable [4]. With a prototype, it will be easier to evaluate the concept and to prepare the future generation with the necessary skills and knowledge needed to operate and maintain this system [34].

The aim of this work is to understand the fundamental vision of Industry 4.0 and develop a smart factory prototype that can be used to showcase and educate people on the concept of Industry 4.0. The prototype is aimed to show the basic concepts of Industry 4.0 such as digitalization, mass customization, data exchange and connecting a production line to the Internet. The prototype was developed by upgrading an existing production trainer and using currently available components [4,14] to show that the Industry 3.0 system could be upgraded to a certain level. This prototype was aimed to be used to understand Industry 4.0 better or help people, especially students and academicians, to have a better overview of Industry 4.0. It can also be used for various training purposes or evaluation by interested parties involved with Industry 4.0.

1.2 Problem Statement

With the increase in labour cost [6,38] and demand for a better life to work quality [1,5], Malaysia needs to break away from its current industrialization policies, adopt new and advanced technologies and look into Industry 4.0 seriously [7,8]. As Industry 4.0 is still new in Malaysia, it is wise to start preparing for the revolution to come by understanding its fundamentals [8]. The key is to understand how Industry 4.0 works and how it could be implemented, especially by upgrading existing systems. The lack of experts and skilled workers in this field means slow progress towards fully implementing Industry 4.0 and this is a big problem as Malaysia will be left behind. Thus, it is important to develop an Industry 4.0 prototype to understand it further and to evaluate the future of Industry 4.0.

The initial cost of implementing Industry 4.0 is very high which is a problem. Most technical providers will recommend new hardware or solutions. This means scrapping old hardware and investing in new systems. Working solutions are currently being made available day by day [8], but the cost is too high and cannot be afforded by the small-medium industry or training institutes [15]. The lack of funding means the lack of equipment, making it hard to train the future workforce with the necessary knowledge and skill competencies. The limited and currently available reference model that shows only part of the concept or application of Industry 4.0 makes it hard for a training institute to invest in this new equipment. It is also harder and less effective to teach students, especially technical and vocational students, to understand this topic when they have to imagine a complex system in their head without a reference model. Therefore, upgrading a currently existing system using currently available components seems to be the best way in terms of cost and time.

Another challenge in developing or upgrading a system into a smart factory system using currently available components is to identify which Industry 4.0

application can be implemented, which off-the-shelf components can be used and how to integrate various systems to work together [5]. There is also an issue on how to connect them to the Internet. Integration of various systems especially from different kinds of manufacturers is a complicated task. Thus, an interface is needed that could interconnect various systems and components preferably using a common way to exchange data.

1.3 Objectives

The main aim of this research was to develop a working Industry 4.0 smart factory prototype as suggested in [4,14,27,39] by upgrading an existing system and using currently available technology that can be used to train students on Industry 4.0. The objectives of this research were as follows:-

(i) To derive a domain-spanning principle solution for a smart factory prototype in the context of Industry 4.0 and implement Conceptual Design Specification Technique for the Engineering of Complex Systems (CONSENS).

(ii) To develop, assemble, integrate and interface a smart factory prototype in the context of Industry 4.0 including its user interface by retrofitting an existing system.

(iii) To evaluate the smart factory prototype in terms of functionality using the *Industrie 4.0* toolbox of the Mechanical Engineering Industry Association (VDMA).

1.4 Scope and Limitation

This work is focused on developing a smart factory prototype to show the basic application of Industry 4.0, especially the concept of mass customization, data exchange and remote access through the Internet. This is as suggested in [4,5,14,27] and to be showcased and used as a training aid. The scope of this research was thus limited to developing a smart factory prototype by upgrading an existing modular production trainer and use currently available components to limit the cost. This research was divided into three phases. The first phase was to derive a domain specific principle solution and to implement a conceptual principle model using

CONSENS [40] to create a system model. Creating a model would ease the development process. It was to give an overall view of the system before attempting to build it.

The second phase was to upgrade an existing production trainer by reassembling it according to its new function and integrating all of its components until it became fully functional. In this project, a smart factory system was set up with a modular and decentralized production concept [14,17] and was equipped with Radio-Frequency Identification (RFID) technology [41]. Products that were assembled by this prototype were modular in form or in other words, can be mix and match to give consumers the liberty of choosing what they want. It was controlled by PC-based controllers which were interconnected in a local area network (LAN) managed by a router with an Internet connection. A server that hosted a supervisory control and data acquisition (SCADA) software and database was also hooked up to the LAN. The SCADA was used as an interface to display, monitor and control the system either locally or through the Internet. The SCADA software was the backbone of the whole system used to integrate all the components and provided an interface between the systems to a database. Lastly was to evaluate the system in terms of functionality and to determining the level of Industry 4.0 it has achieved. For this, the Toolbox *Industrie* 4.0 of VDMA was used [36]. This prototype was later used to train students and showcased to get feedbacks. Other than that, an observation on the skill sets needed to operate, develop and maintain the system was conducted.

In this research, not all of the nine pillars of Industry 4.0 were adapted. Rather, it was limited to the existing system and the components available at hand. It focused on the digitalization of signals, IoT for monitoring, cloud services, data exchange and integrating various systems. It also showed the concept of a modular product. Thus, big data and analytics, simulation, augmented reality (AR), and additive manufacturing was not covered directly in this project as they are big topics and they could be a research topic on its own. To cover the topic of data analytics, new algorithms need to be created. The simulation includes the development of software that could mimic the physical world and requires a lot of animation. This is also the case for augmented reality. As for additive manufacturing, with the current equipment, it is not viable to include 3D printing in this prototype. Another important topic and a big concern in Industry 4.0 is cybersecurity. As the topic itself is a big topic on its own, it was not covered in this research although basic security was implemented. Other than that, a digitalized mimic of the physical world was not implemented but the input and output signals of various components were displayed on the HMI. Again, to develop a mimic of the real world requires a lot of animation and software development and is more suitable for a software developer. The relevant scope of this work is as follows:

(i) The smart factory prototype consisted of two parts: A domain specific principle solution with a conceptual model developed by implementing CONSENS and a working prototype.

(ii) The prototype was developed by upgrading an existing system using currently forehanded available parts and components to limit the cost. It consisted of three production stations equipped with RFID technology and using Industrial Ethernet.

(iii) The system including the controllers and server were interconnected with each other through a LAN managed by a router connected to the Internet. The server hosted the SCADA software and database.

(iv) The SCADA software was used as the backbone of the system to interconnect them together and link it to a database. An interface for local and remote access for displaying, monitoring and controlling data was also developed using this software.

(v) The smart factory prototype was able to produce a final product that is modular using the mix and match concept and is able to produce up to eight (8) variants without any reprogramming to show the concept of customization.

(vi) The evaluation was to test the functionality of the system, the level of Industry 4.0 compliance according to a toolbox by VDMA.

(vii) In this research, not all of Industry 4.0 pillars were implemented, for example, the cybersecurity of the system was covered, the digitalized mimic of the physical world was not developed and none of the data obtained for example the digitalized signals was analysed. Among others, this is because to include all of the Industry 4.0 pillars in one prototype will involve a lot of time, cost and effort and the goal of this research is to develop a prototype using currently available components to minimize the cost.

1.5 Significance

Industry 4.0 is the next revolution and has yet to be widely implemented [22]. Therefore, the potential for such a system is still vast. Furthermore, to compete globally [4,7] the implementation of Industry 4.0 is crucial [4,7] as the local market shares are limited and this is a great opportunity [8]. The smart factory is one of the applications of Industry 4.0 [4]. With the winds of change present in the global economy through a better supply chain and changes in consumers' buying habits, countries that do not take action will be left behind. Malaysia has taken a step forward by introducing the National Industry 4.0 Policy Framework launched by the prime minister in 2018. This makes Industry 4.0 a national agenda. This policy was published by the Ministry of International Trade and Industry (MITI) [7]. According to this policy, the manufacturing sector in Malaysia contributed 22% of the Gross Domestic Product (GDP) in the last five years with over two million employees in this sector. With the emergence of new technologies at a more affordable cost [23,24], machines and automated systems will replace humans. With a smart factory, mass customization, higher productivity, and products with good quality can be produced at a reasonable cost [5,19]. This means that cheap labour is no longer an investment factor [8,22] and investors are looking for countries that could provide the technical know-how and skilled workers to develop, operate and maintain such systems. To do this, an awareness campaign to increase the understanding of Industry 4.0 must be carried out, for example, using a prototype.

From a survey conducted by Acatech, 84% of the respondents agreed that Industry 4.0 has a potential future [42]. A survey by the Germany Trade and Invest (GTAI) indicated that 81% of the respondents responded with 'yes' to the question of whether Industry 4.0 will offer new opportunities [43]. The survey showed that Industry 4.0 has a vast potential and will create new opportunities or a business model that will one day influence the industrial world. The Malaysian government has targeted an annual GDP growth rate of 5.1% under the 11th Malaysian Plan (RMK-11) for the manufacturing sector [7]. This shows that manufacturing is an important element of the economy.

Although the smart factory is highly automated and it seems like machines and robots are filling the employment list, skilled workers are still needed to operate and maintain these automated machines [20]. Skilled workers mean higher income that will make the economy flourish [35]. Another aspect related to Industry 4.0 is the Economic Transformation Program (ETP) in the sectors of electrical and electronics [44]. The target is to revitalize the industry, accelerate higher yields and prepare the industry to respond to external shocks such as any decline in global demand. This is to move the industry away from manufacturing activities towards higher-value activities such as design, assembly, packaging and the provision of total solutions. Industry 4.0 gives the opportunity to do this. Manufacturing will be automated and time can be focused on research and designing new products [4].

According to the National Industry 4.0 Policy Framework, among the challenges faced by Malaysia are the lack of awareness, the need to enhance the skill of workers and the high cost of investment [7]. Therefore, it is important to expose trainers and academicians with Industry 4.0-related technologies and skills to develop the know-how and expertise in this field. After that is to train the current and future workforce to adhere to these changes [7,8]. By doing this, students can have an oversight of what is to come. Educators need to understand Industry 4.0 so that they could incorporate this concept into their teaching syllabus [30]. All of this must be done at an affordable cost and possibly by using equipment that is already available on the shelves. One way is to upgrade existing systems with Industry 4.0-related technologies.

Therefore, this prototype is significant to create awareness to understand Industry 4.0 better. This is to see how it works and whether Industry 4.0 is relevant. It is also to identify the relevant skills needed and adapt the current curricular for training as suggested in [4,34].

1.6 Thesis Organization

This thesis is organized as follows. CHAPTER 1 highlights the background of this project, problem statement, objective, scope and its significance. CHAPTER 2 deliberates on available literature on Industry 4.0, smart factory and CONSENS. CHAPTER 3 explains the methodology used in developing this prototype, the design, and the evaluation method. CHAPTER 4 explains the result of this research which is the prototype itself including the CONSENS Model, the operation flow and the interface. CHAPTER 5 discusses the result of the evaluation and its analysis. CHAPTER 6 discusses the conclusion and future potential of this project.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews available literature concerning this research. Reviews are focused on Industry 4.0 as the central point of this research including its driving factor, fundamentals, benefits, and challenges. This chapter also focuses on the smart factory concept as it is the output of this research and CONSENS which was the specification technique used.

2.1 Background of Industry 4.0

Today, the Internet is used widely in various sectors to connect people around the world [17]. Therefore, the next industrial revolution should involve the Internet [2,17,23], thus Industry 4.0 was introduced, which is part of the Internet of Things (IoT), Internet of Data and Internet of Service hype but for the industry [4,20,28]. Big data analytics and cloud computing among others will be integrated into the overall supply chain leading to a smarter and more decentralized factory [28].

The term Industry 4.0 was first used in 2011 [9,23,26,37] during the Hannover Fair in Germany which was called “Industrie 4.0” [4]. The German research union for economy and science proposed and asked for funding from the German government to start a research program on the use of computers in the industry. It aimed to maintain the technological edge of the German industry as Germany was the leading supplier of manufacturing equipment and expertise [4,20,23,28]. Most people say that Industry 4.0 is a subset of the fourth industrial revolution which was widely used since 2016 during the World Economic Forum. Figure 2.1 shows the industrial revolutions from the first industrial revolution to the fourth industrial revolution.

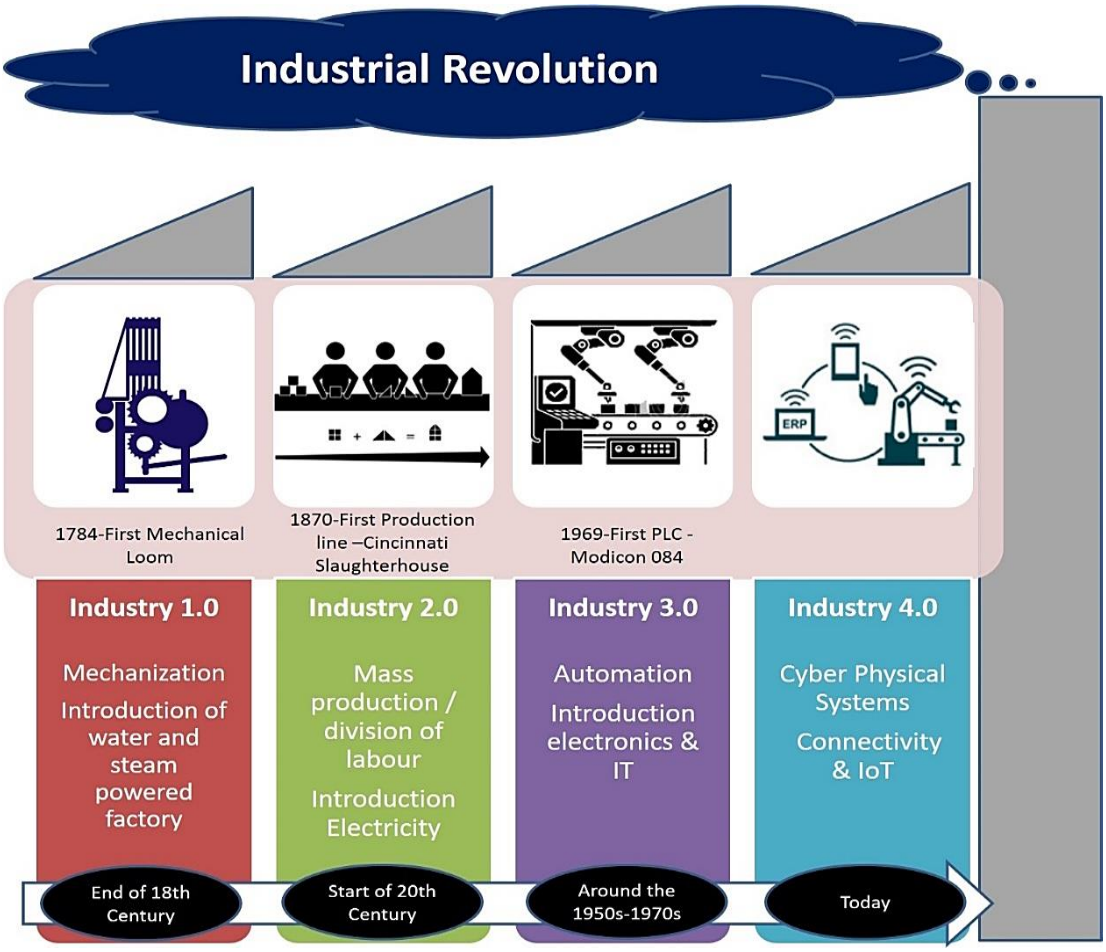

Figure 2.1: Industrial revolutions from the first to the fourth

The first industrial revolution was said to have started between 1760 and 1820 [4,37] or the 18th century [31]. During this period, new inventions were created and people began to explore the world. This led to a demand for goods to increase. During this era, the introduction of water-powered machines and steam power caused the revolution [27,28]. Mechanization and simple mechanical machines were created and enhanced to a create an industrial machine that could operate longer, powered by water or steam engine [2,20,32,35,37,45]. This was the start of industrialization in which factories were built. This era was associated with the textile industry and one of the examples of the machines created at this time was the first mechanical loom in the year 1784 [4,20,22,23,30].

The second period of the industrial revolution began in the 20th century [2,20]. Some say it started around 1870 [22,31,37] with the first production line at Cincinnati Slaughterhouses [23]. But the famous and most remembered assembly line was started by Henry Ford [20,23] in 1913. This was the age of division of labour, mass production, and electricity [22,27,28,32,35,45] in which assembly lines were set up to produce goods or products in mass quantity for mass consumption. In an assembly line, the production process of a product was distributed into a few stations. Each station assembled parts of the product. Mass production means products are not uniquely made for a certain individual but are made in batches with each batch of the product having the same specification. One of the famous phrases by Henry Ford was, “Any customer can have a car painted any colour that he wants so long as it is black”. Another thing that happened during this period was the introduction of electricity that changed mankind forever [30]. Electricity paved the way to numerous new inventions powered by electricity, including machines and lights. It made machines more energy efficient and safer rather than using steam power.

Around the 1950s to 1970s, after the World War, the third industrial revolution began. This was the age of electronics and IT [2,20,28,31,32,35,37] due to the founding of semiconductors that made way to the introduction of electronic control systems, computers, ICT and later advancement in software. Mechanical machines could be electronically controlled, making way to the beginning era of automation [30,48]. In this era, parts of human responsibilities at work were overtaken by machines and robots. This has led to an increase in productivity and consistency in quality by eliminating the human error factor. Production processes were more efficient and optimized thanks to the advancement in the sensing drive system, control, and programming. One of the examples was the creation of the first programmable logic controller (PLC) [2] in 1969 [22] by Modicon [23].

The fourth and current revolution is currently in the making [36]. Since then, plans and workgroups were carried out and reports on this topic were published. One of the workgroups was led by Prof. Dr. Henning Kagermann, President of Acatech, National Academy of Science and Engineering. This workgroup presented a report called “Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 Working Group” in April 2013, which was sponsored by the German government [4,20]. This report was one of the earliest references used to develop Industry 4.0 [46]. The key point of this revolution is the Cyber-Physical System [32] in which digitalization, data exchange between systems [20,33], and analytics are part of the framework [4]. Machines, the logistic system and the building management system will be linked to the Internet [4,20,30]. The

Internet will be used as a data exchange medium and these data are mostly stored in clouds which offer various services, for example, machine learning, analytics, dashboard display, and database services. With all these data, production processes could be analysed and enhanced. Products of the future are also revolutionized and customized according to individual desire and needs [22]. Products are customizable or modular and will have its own identification number or address, making it capable to exchange data with a machine [47]. This identification will also be used for aftermarket services, for example to provide feedback to a manufacturer. The aim is to overcome challenges in today’s manufacturing related to productivity, labour cost, energy efficiency, quality, consistency and demographic changes [4,28]. With most of the manufacturing system automated and monitored by AI, workers can be more creative and focused on the development of new ideas and products.

2.2 Fundamentals of Industry 4.0

Industry 4.0 is aimed to interconnect and create a collaborative interaction between humans, machines, logistics, materials, production, maintenance, sales, after sales, marketing and any other element along a value chain to create intelligent networks that transfer data between each other [20,27]. The design principles are interconnection or interoperability, transparency in information, technical assistance, and decentralized decisions [31]. This is called the Cyber-Physical Systems [4,32].

The main concept is connecting the physical world to a digital copy [4,20] or in other words, digitalizing or virtualizing the physical world to create a digital twin that would mirror the physical world in real time [20,28,29,31,32,39]. This involves a lot of sensors to be equipped in the physical machines for it to be displayed in the digital world [19,22,27,29,31,46,48]. Also, a data acquisition system that could convert digitalize all of these signals. Here, machines, production lines around the globe, products and workers will be interconnected and can communicate with each other [2] in a networked society [22] and be linked to the Internet [20,23]. Users could monitor and control many things through the Internet or local network at nearly real time. Data can be transmitted or received through the Internet and could be linked with various cloud services such as machine learning. The whole system is constantly monitored [30] so that it could be optimized and problems could be detected early to avoid downtimes [20,22]. With the rapid change of products, this virtual copy can be used not only for monitoring but also for planning and simulating new products before it is transferred to the real world [20,25]. The simulation process is very important nowadays as it can cut the cost of manufacturing, reduce time to market, reduce errors and increase quality. The aim is to create a virtual environment of the physical world so that all simulations could be done to rectify problems and errors, fine-tune production processes, and find the best parameters before or during a production process anywhere in the world [19,20,21]. Figure 2.2 shows the Cyber-Physical Systems.

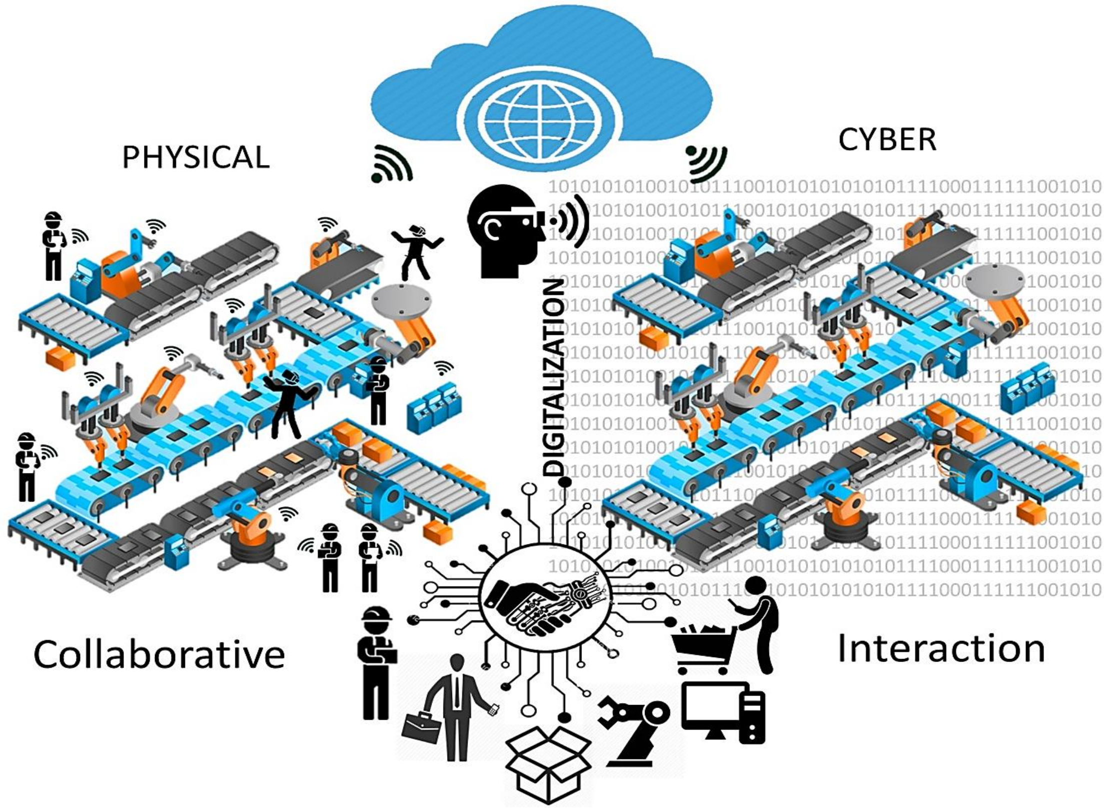

Figure 2.2: Industry 4.0 fundamentals

Digitalization in Industry 4.0 also means that guided procedures could be displayed at real-time using smart devices such as smartphones or watches to assist workers in carrying out their jobs [4,33,39,51]. Workers need to follow these guidelines and if a process is skipped, the system will not allow them to continue to the next task. This will make the production of variants of product easier in which a worker only needs to follow the guided visual SOP every time there is a new product

[17]. This method is not only to show how to operate a machine or assemble a product but can also be used to carry out simple diagnostics, repairs and preventive maintenance. Digitalization will also mean that the whole production line including the products will be digitalized in 3D drawings.

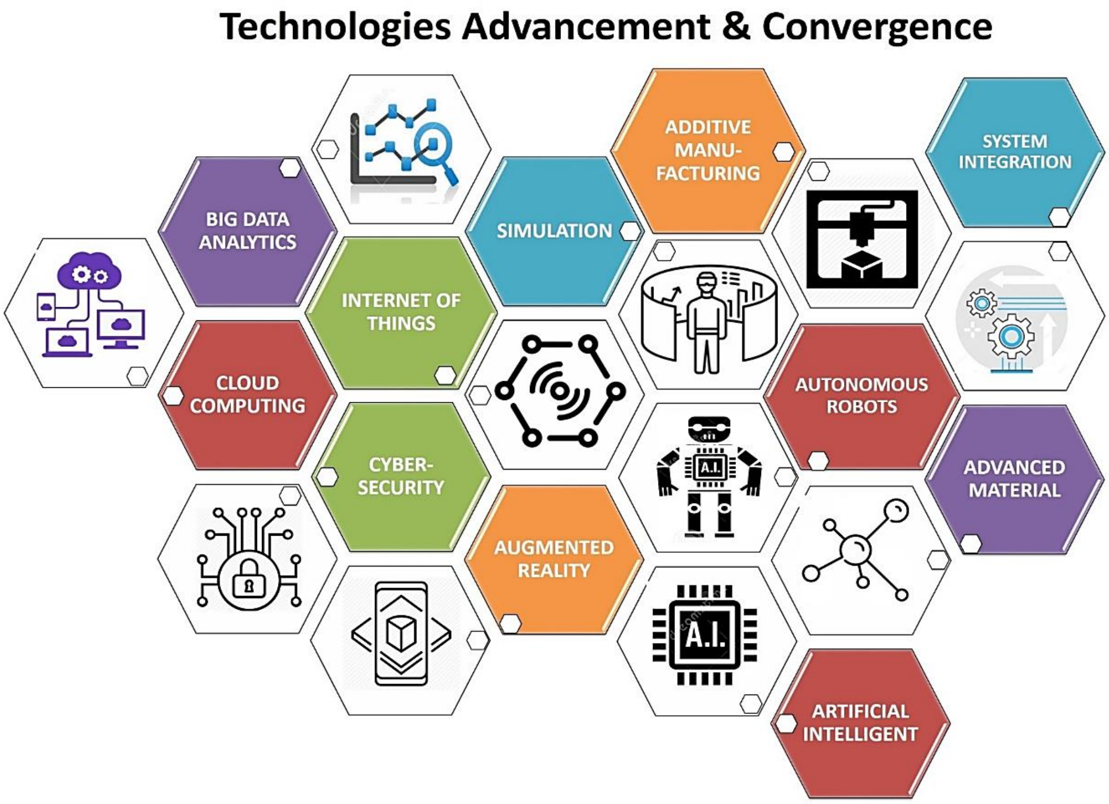

Figure 2.3: Key components of Industry 4.0

Figure 2.3 shows the eleven pillars of Industry 4.0 according to Malaysia's National Industry 4.0 policy [7]. In many cases, there may be fewer or more pillars according to each organization's interpretation. These are technologies that support Industry 4.0. Among the technologies are autonomous or intelligent robots, simulation, horizontal and vertical system integration, IoT, cybersecurity, cloud computing, additive manufacturing, augmented reality and big data analytics [4,5,20,51]. Some of these technologies already exist but are not used widely due to factors such as cost and readiness [22,23].

Big data and advanced analytics [20,51] are needed to support the enormous available data [22] at real-time [5], especially from various devices and connected things [45], including the digitalization of a smart factory [30]. Data from various sources such as a production line are monitored by adding sensors to capture the data [50] or by using a data mining algorithm. These data will then be analysed correctly to get useable information [32,48]. This is called advanced analytics. Data are captured continuously and analysed to improve the production process and the product itself [5,20,37,48,49]. Sensors are not only used to trigger an event or process or sequence but are also used to monitor the process, quality of the product, monitor the machine's parameter and components, and also its usage [2,20,49]. Big data is needed to transfer accumulated data into the digital world mainly through the Internet to be analysed and monitored [22]. These data can also be stored in cloud storages and be manipulated using various cloud services such as machine learning, analytics, and business intelligence. Big data enables a large amount of data to be transferred, stored and processed.

Cloud computing is related to big data and analytics. Cloud computing is a method of using a networked and remote computer connected through the Internet to store, manage, and process data, rather than using a computer onsite. Various services are provided by cloud service providers [29,30]. With cloud computing, a computer onsite does not need to be a high-end computer or is scalable [5,22,25]. Most of the computing and data management is done in the cloud and is accessible anywhere at any time [5,19] provided that there is an Internet connection. Cloud computing is a type of service in which one has to pay a subscription fee. This is related to IoT and IoS [5,48] which is said by [4] to have initiated Industry 4.0. With the advancement in the Internet, IoT focuses on getting everything connected to the Internet with their own address or IP [9] to exchange data for various reasons such as monitoring, remote access, updates, and alarms [29]. Everything means anything from the television at home, to cars, building management systems and even machines in a factory where anyone can exchange data anytime, anywhere and subscribe to any service [45]. Connecting these devices allows for information sharing and communication between devices [45]. With all of these connectivity and data exchanges, a big problem that arises is data and access security [5,17,20,43]. This is why cybersecurity is a big concern in Industry 4.0. It is to safeguard data and avoid computers from being hacked [5,22,37].

The next big thing is the simulation [20]. Nowadays, there has been a big leap in software development and computing power, making simulations of various systems from electrical circuits to mechanical movement possible. Simulations nowadays are needed to reduce development cost and time. A system can be simulated first and a solution can be obtained before it is applied to the real world without having to stop the production line [20,21]. Other than that, virtualization using augmented reality (AR) or virtual reality (VR) will also be used for various reasons such as an interactive data display [2]. AR is an extension of VR. AR means enhancing the real world by inserting graphics, animation, sound or even feedbacks. It can be used to replace manual books or SOPs with interactive guided graphics. It could also be used to display various data from a machine just by pointing a device like a smartphone to a target or marker on the machine. Simulation combined with AR and VR can be used for training purposes to prepare the new workforce or the existing workforce before they even carry out any actual work on the factory floor. For example, by using a tablet, a user will just have to scan a target on a machine, and certain real-time information of the machine is displayed on the screen.

To create a customized product, the product must be individually designed and fabricated. This is not cost effective at all. One of the solutions is by creating a modular product [2] in which consumers can mix and match a product according to a specific palette. Another solution is by using additive manufacturing to create customized products or low volume products [2,20,46] at an affordable cost [22]. Additive manufacturing used to be associated with producing prototypes [22]. It is a manufacturing process in which a product is made layer by layer from nothing as opposed to the conventional process of subtraction from material which allows for a more customized and complex design [2]. Nowadays, it is not only products from thermoplastics that could be made this way, but also food, ceramic-based materials, living cells, and metal alloy products [22]. Additive manufacturing or 3-dimensional (3D) printing starts with a Computer Aided Design (CAD) drawing. The drawing is then converted into layers [22] and printed using a 3D printer. 3D scanners are also used to scan objects for mass customization [51]. An example of its application is that one can scan one’s foot and fabricate a perfectly fitted shoe, for example, using a 3D printer.

Advanced robotics is also being looked into. Robots have been around for a very long time. The difference is that robots of the future will be more intelligent, autonomous, flexible and can collaborate with each other or work side by side with a human [20,24,25,44]. This is called the Cobot or Co-robot for collaborative robot [27]. The robot can also make decisions without the help of humans. For example, a mobile robot could avoid an obstacle and set its own new path to get to its destination. Another example is by using machine vision to locate an object or identify an object for assembly.

Then there is the vertical and horizontal integration. Horizontal integration is to interconnect all the mentioned above technology including devices such as sensors, actuators and controllers [5] on the production floor with each other [20] throughout the supply value chain. Vertical integration, on the other hand, is to integrate different hierarchical levels of a business such as the production floor with the business management and resource tools [46] such as production planning, Manufacturing Executing System (MES), Enterprise Resource Planning (ERP), and database. In other words, it is linking and interconnecting various vertical and horizontal systems or using one system to monitor and control the production line together with the enterprise aspect such as sales. End-to-end integration, on the other hand, is a process of chaining all activities in a product life-cycle from customer requirement, design, development, planning, production, after sales up until the recycling of a product [5,22,44]. This needs to be done across the value chain.

Two additional pillars are AI [5,7] and advanced material [7]. AI is the ultimate goal of Industry 4.0. It can be associated with machine learning in which a machine will learn from experience [29]. It can be applied to a robot or a production system. With all the available data and analysis that has been carried out, an intelligent system could decide on its own on how to handle certain things [5]. For example, the system will gather information from the Internet on current cloth trends and decide what colour of cloth to produce in the production without any interaction or input from a human. Advanced material, on the other hand, is the study of the various types of materials that could be used in a product, mainly focusing on eco-friendly materials. Among others, it is to find suitable materials that can be fabricated using 3D printing technologies for customization.

2.3 Transformative Drivers

Figure 2.4 shows the enabling factors that lead towards Industry 4.0 implementations according to the Malaysia National Policy on Industry 4.0. As can be seen in figure 2.4, the four main factors are technological advancement, global economic order, knowledge and skills, and global supply chain. These factors have encouraged the introduction of Industry 4.0 on a global scale.

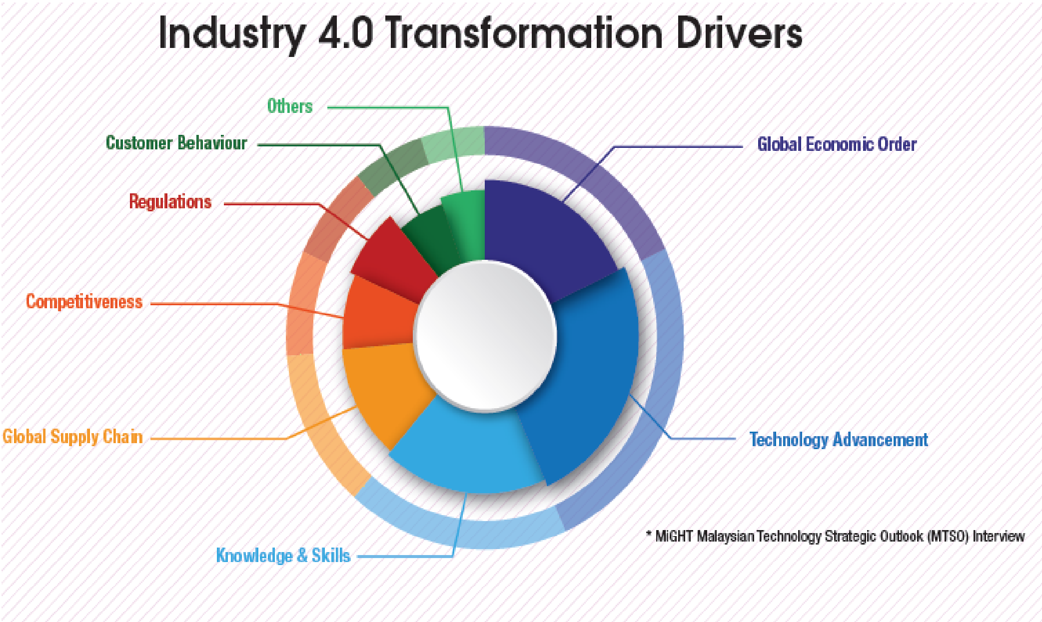

Figure 2.4: Factors leading to Industry 4.0 [7]

Today's trends and technological advancements have created a disruption in people's lives and how industries operate today [35]. Many new research and innovations today have led to the introduction of new technologies and systems that create a disruption in life [19,35,39,50]. These technologies are also becoming more affordable [2,22,27]. One of the examples is smartphones. Owning a smartphone nowadays is a must, and with an Internet connection, it could open many possibilities that ease our daily routines. Smartphones are not only used for calling and texting, but also for various things such as monitoring and controlling a production line. New technology trends such as big data analytics, cloud computing, and IoT could be deployed directly from a smartphone. Another disruptive technology is 3D printing. 3D printing is an additive manufacturing in which a product is produced layer by layer. Additive manufacturing has opened the possibility to create customized products or a product specifically for one user.

The past decade has also seen rapid development in computer technologies in terms of computing power, size, cooling capability, energy efficiency, and cost. In the 90s, computers only had one core with the capability of running 6.4 million instructions per second (MIPS). Nowadays 16 core processors running 318000 MIPS

[8] are available for the masses at an affordable price, opening the opportunity towards digitalization. This aligns with Moore's law which says that the speed and capability of computers can be expected to double every two years, and consumers will pay less for these computers [52]. Software development has also been rapidly developing, making artificial intelligence (AI) possible. Robot technologies are also advancing ahead with the integration of AI, leading to autonomous decisions made by the robot itself. Robots are not only used in the industries, but also in houses, and this is a good thing in which consumers can now afford to have a robot.

Internet connects people [9,12] and has brought the world closer [17]. The number of Internet users and devices connected to the Internet is increasing by the day [11,48]. As for that, the current Internet Protocol Version 4 (IPv4) which is the address assigned to each device is nearing its limit in term of the number of devices it could handle. To overcome this problem, the introduction of Internet Protocol Version 6 (IPv6) has enabled even more devices to be connected to the Internet enabling the vision of IoT to connect as many devices as possible. The Internet has led to several changes in our daily routine [45] with the introduction of various trends, for example, the trend of e-commerce or online shopping [10,11,46]. The use of social media such as Facebook and Whatsapp has also increased. Internet-based companies have gained ground since the last decade. According to Interbrand's 2018 Best Global Brands, Google, Amazon, and Facebook are ranked as the top ten in the best global brands [53]. With high demands on the Internet, communication infrastructures have been rapidly upgraded, making the most of the world digitally interconnected with high-speed Internet possible [10]. With the increase in Internet speed and the decrease in monthly subscription costs [23], many new inventions, technology, and services related to the Internet have been introduced.

Another transformative drive is the need for higher productivity [20], the flexibility of the production system [32] and the reduction of waste in resources by manufacturers especially to adapt to the current dynamic market and to stay competitive. This is related to the new global economic order. The introduction of the smart factory with highly automated systems, advanced manufacturing processes, ICT and advanced data analysis could increase the efficiency of a production line or process that will result in improvement in productivity levels at a lower cost per piece [19,20]. Machines could run non-stop even without human presence [20,26]. Machines are more intelligent and could decide and organize simple things on its own without the need for human assistance. In an event of a breakdown, the system can divert the normal route of the workpiece in progress so that production can still continue [32]. Processes are simulated before it is physically produced and could be monitored and controlled along the process. This will lead to the optimization of processes [20]. With the increase in productivity and optimized processes as well as effective use of resources such as energy, labour, and material [25], an increase in revenue can be expected, and a better environment and better usage of resources can be achieved. Smart factories are interconnected through the Internet. This will enable remote monitoring and control of a production line [5]. One could also carry out remote debugging and repair if necessary [5] and it is also possible to guide someone on site to carry out machine repairs. Climate change and the environmental movement is also a driving force. To address these concerns, smart grids and a smart building system can be applied to save energy and help save the environment [5].

The world population has reached 7.6 billion and rising. It is expected that there will be more demands due to the increase of the world's population and the buying power of the consumers [46] due to the increase in wages [6]. Each of these individuals has their own preferences and desires. This leads to manufacturers needing to create numerous variations of a product in order to satisfy each targeted group of consumers. Therefore, a product of the future needs to be customizable according to one's likes and dislikes [2,4,17,22,37], and consumers will be actively involved in determining the specification or criteria of a product they want [22]. A product can also be created to be more modular [47] and individualized according to the customers' needs [2] if it is not fully customizable. A product can be mix-and-match thanks to modular product design or custom-made using additive manufacturing [2]. A simple example is a kitchen cabinet. A customer can choose the design, material, colour and style, and also plan the production date to suit the delivery and installation date. These kitchen cabinets are individualized according to customer's preferences because the mix-and-match process creates a highly specific product for each customer. This is possible with the modular design of today's kitchen cabinets. It will offer diversity for customers to create a more personalized product [8]. It will also make it easier for customers to change or upgrade the products that they are currently using.

Other than that, the product life-cycle is also getting shorter [14,17,19]. Consumers nowadays are easily bored and with new technologies emerging, they are always looking to have the latest products in the market or upgrade their old ones. Therefore, manufacturers need to adapt to this trend by regularly updating their products or introduce something new in order to stay relevant in the market [2,17]. The increasing number of variation is complex to manufacture [2,26] in terms of planning, quality, and reliability [17,46]. Other than fulfilling individual desires [4], the cost of a product must still be affordable in order to be sustainable. This is hard to achieve as product variation will increase production complexity that leads to higher production and material cost, which affect labour arrangements, increase the lead time and cause inconsistency, especially in the quality of a product [54].

In term of knowledge and skills, human has developed many new technologies and acquire a lot of new knowledge by the day. This has led to an increase in people equipped with the knowledge and skills sets related to Industry 4.0's fundamental pillars. Among others, this is because related subjects are nowadays taught in schools and colleges [24]. Thus therefore, the implementation of Industry 4.0 can be carried out with ease although specific skills are still needed in order to implement Industry 4.0 holistically.

Postal services were nearly relinquished with the introduction of texting and emailing, but boomed back when e-commerce gained ground [10]. Nowadays, the supply chain does not only cater to domestic demands but has become very dynamic, making the world borderless and not bound by geographic location [7,45]. The network of supply chains around the world is very complex yet efficient, making the distribution of material or product effortless and fast. To keep a peace of mind, the enrooted product is also traceable online [26]. This has helped e-commerce to grow rapidly around the world.

Nowadays, workers are demanding higher wages, balanced life to work conditions, flexible working hours, and a better and more ergonomic working environment [5]. This has caused an increase in labour cost throughout the years [6,38]. Other than that, the ageing population or workforce [5,14] due to better health care nowadays have led to fewer opportunities for the younger workforce. This is an increase pressure on manufacturers and has influenced governments to change their policies in favour of the workers' demands. Other than that, the advancement in technology with the integration of ICT in manufacturing has caused a disruption in the workforce [22,25] and the skill set that workers need to have [37]. Factories are running on their own and can be automatically monitored remotely. Therefore workers can concentrate on more important tasks such as on designing and developing new technology or innovating existing technologies to make it more efficient and dynamic [20]. Heavy, difficult, dangerous and dirty jobs are mainly done by robots or machines which reduce the risk of injury and increase productivity [24,25]. A workspace can be constantly monitored autonomously. Monitoring is not just limited to the production process or a product's quality, but also applies to the safety of the working area around it especially with the presence of human beings in high-risk areas such as a robot's workspace. The process is immediately stopped if a human's presence is detected and will automatically continue when it is safe.

Workers' roles will change from being general workers into semi-technical workers that could not only operate a system, but have the technical ability to monitor, carry out simple maintenance, repairs, and do management work; thus more skilled workers are needed [19,35]. Visual guided standard operating procedures (SOP) will help workers carry out different kinds of task with ease [20,47], known as augmented operators [17]. All of these could indirectly impact workers' lives, for example, in the increase of wages and giving a balance between life and work due to flexible tasks and working hours [54]. Other than that, the workforce will be more dynamic, diversified and flexible [4,17,47]. There will also be increased employment opportunities in the ICT sectors. New software, web applications, web services, networking, telecommunications, cyber-security and animation for AR are needed to complete an Industry 4.0 system.

2.4 Challenges of Industry 4.0

A revolution always encounters a lot of challenges at its beginning phase. These challenges may hinder the progress of a revolution. The first challenge, of course, is to understand what this revolution is and the return of investment that could be obtained [26]. Large amounts of investments are needed [27,37] and are always the main concern of a manufacturer. This is also because current devices such as the PLC can still be used and there is no point of investing in new technology without any significant improvements [55]. Though it is thought to be beneficial, manufacturers still need to consider the return of investment before taking the step forward. Automation will cost money, and automating an entire production or value chain will cost a lot of money. They also have to consider the investment to train the workforce.

The next challenge is the demand for an upgraded workforce [4], especially for SMIs that are not familiar with high technologies [34]. The competencies that are needed in developing, integrating, operating and maintaining Industry 4.0 systems are different than what is currently available and cannot be easily learned in a classroom [22,34,37]. Workers need to be flexible and have various competencies such as automation and ICT [46]. Their roles will change and broaden more than before as the level of automation increases. Workers need to be upgraded and retrained with Industry 4.0-related competencies [22] for companies to stay competitive [14]. Other than that, experts related to Industry 4.0 are needed to train future workforces. The current curriculum needs to be overhauled and embedded with Industry 4.0-related competencies. Training providers also need to prepare related equipment for training.

Another challenge is the availability of Industry 4.0-capable systems and machines [5]. Solution providers, developers and system integrators will have to provide or develop a platform, device, and solution to support Industry 4.0 in order for this revolution to kick off. Machine and systems manufacturers need to step their game up to keep up with the demand for machines and systems that support Industry 4.0. This means that current suppliers and developers must invest more in creating a viable system and be more engaged with information technology and how it will be incorporated into the manufacturing systems that they come up with. Developers could also figure out a way to integrate or upgrade the current system for it to comply with Industry 4.0 requirements. This is to save cost.

Standardization across industries is also a big challenge [4,17,22,25,45]. This includes the standard definition, curriculum, communication protocol, and other related topics. Standardization is needed to guide the industry on certain things and is also important for policymakers to determine who will able to receive government funding. Another important standard that is needed is in the communication field. Current systems will still run as it is, but when they need to communicate, a standard protocol should be used so that they could understand each other. The need for a standard communication protocol is highly demanding [20]. Therefore a standardized language to communicate across the various platforms or a common communication protocol needs to be discussed among the involved parties [22,31]. Thus, manufacturers, users, regulators, and government organizations need to sit together to discuss the standardization of Industry 4.0 and come out with a reference that can be used by all.

Communication for data exchange is very important for Industry 4.0. This will involve a lot of wiring and therefore a suitable Fieldbus system can be used to network various systems and devices such as sensors and actuators [55] to reduce the wiring complexity. In Industry 4.0, these systems should be able to communicate with each other. A new factory should not have a lot of problems as a single communication protocol could be set up right from the beginning, but for old factories that usually have different kinds of communication protocols for each device, it is a challenge to integrate it all because of the various communication protocols. Changing all the protocols or languages into one unified language is not possible due to many factors such as the manufacturer's reluctance to open their proprietary design and the involvement of a high cost. One way is to use an interface that could connect all of these systems. This interface could be hardware-based such as a serial to Ethernet converter or software-based such as using Open Platform Communication (OPC). OPC is a standard communication platform for a secure and reliable exchange of data among various devices from multiple vendors [17][49]. This platform is managed by the OPC Foundation. Using this type of interface will make it easier to communicate with various devices using different types of protocols. The OPC will act as a translator that can translate one protocol to another.

One of the main concerns of Industry 4.0 is cybersecurity involving data security and access risks [5,17,23,25,27,37,43]. The use of the Internet means that machines are subject to cyber-attack, misuse of data or data leakage [5,22,37]. Data security is a big issue in implementing Industry 4.0 as systems will be sharing the Internet around the world with everyone and everything [37]. Therefore, cybersecurity solution providers will also have to step up and develop better security systems to protect Industry 4.0 systems from caving under the pressure and threat from potential viruses, cyber-attacks or data leakage. Cybersecurity solution providers also need to develop various solutions to ensure the safety of things connected to the Internet. On the other hand, communication reliability and infrastructure is also a big problem [20,22]. Investment also needs to be made in the field of communication reliability and infrastructure to ensure data transfer is done smoothly, promptly and without any data loss which could cause a lot of trouble. The infrastructure needs to be able to support stable big data transfer without lost. Any interruption in the network could lead to disruption in production. Therefore, the Internet and network providers need to ensure its reliability before Industry 4.0 could be implemented.

2.5 Implementation of Industry 4.0

To implement Industry 4.0, it must be done in stages [55]. Figure 2.5 shows the steps of implementing Industry 4.0 systems starting from the monitoring of data, control or triggering an event, analysis of data and lastly to create an autonomous system. Automation devices or systems must first be able to communicate or in other words exchange data between systems, devices or interface [55]. The first step is to acquire data from a system, device or source. The data source could be from a programmable logic controller (PLC), a microcontroller or any input/output (IO) device [56]. The main idea is to be able to monitor and display these data on an interface. The next step is to be able to control these IO from an interface. With this, certain functions or IO of the system can be controlled, thus event or scheduled triggering can be carried out. The next step is to analyse the data received and transform it into usable data for various functions, for example, predictive maintenance or diagnostics. The last step is to create an autonomous system in which the system can make decisions and carry out the decision autonomously.

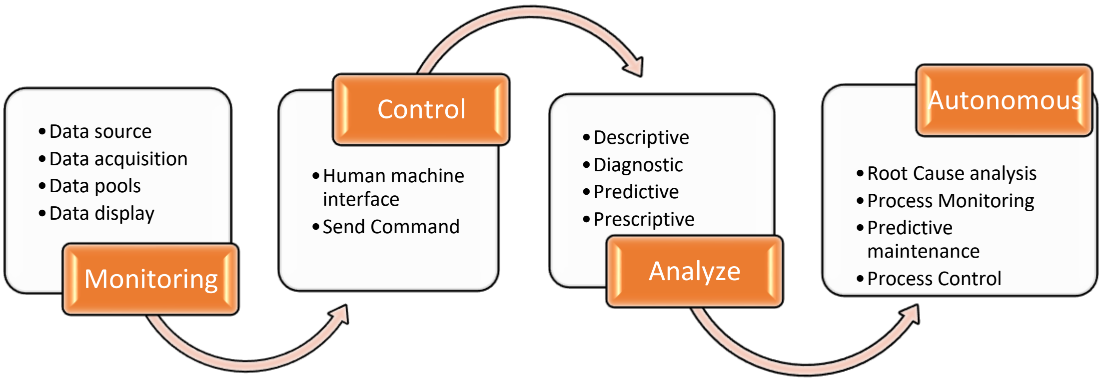

Figure 2.5: Implementation stages of Industry 4.0

2.6 Smart Factory

The term smart factory has a lot of interpretation [47] and has been around for some time now. It is said by [4] to be the key feature of Industry 4.0. A survey conducted by Acatech on the understanding of Industry 4.0 indicates that more than 94% of the respondents chose the smart factory as a key element of Industry 4.0 [42] and 74% chose the smart product [42]. This shows the importance of the smart factory. In Industry 4.0, a smart factory means that the manufacturing processes are not just automated, but are also interconnected, intelligent, dynamic and flexible [9] in which machines are equipped with self-optimizing and self-regulating functions and can decide on its own certain thing [5], for example, when it should be restocked [26] or when maintenance should be carried out [50]. Machines could function on their own without the need for workers to carry out routine tasks [5,24]. It will be linked globally to various departments such as facility management, logistics, warehouse, quality, and maintenance. It will have the capability to compute, communicate and control [5] and interact actively with humans. Automation will be implemented throughout the factory [20,28]. Smart facility and power management are also implemented in the factory. Machines will be able to make decentralized decisions [5] and not depend on humans input only.

A smart factory is an interconnected factory. Machine to machine (M2M), machine to products, and human to machine interaction or communication is important and some of this will happen automatically in real time. The machine will be able to automatically exchange information [4,20,25,33] with other machines, triggering events and controlling each other independently [31]. For example, machines could send an alert to any department if an error occurs or if it runs out of materials. Workers from a different hierarchy level, customers, production system including machines, sensors, actuators, social media and other resources will be interconnected with one another, exchanging data [9] and communicating [25] in real time [29] using an interconnected network [22] like a social network [37], creating more dynamic relationships between workers, resources, customers and systems [29,47], turning them into social machines [4]. Data could be transferred from one machine to another, making the production operation smoother, faster and more efficient. Furthermore, the factory is interconnected through the Internet. With this, machines in a smart factory could also be monitored and controlled remotely in real time [37]. This means that the production line can be controlled from outside the compound or the maintenance procedure could be done remotely [4,5].

Another criterion of a smart factory is that the manufacturing system will be very flexible [5,9,45,47] to adapt to the current volatile and dynamic market situation [29,47] and complexity of a product and supply chain [25,34]. Flexible manufacturing could adapt better to product updates and changes [17,37] without compromising on delivery time, productivity and quality [54]. The production line must be able to adapt to the current product that it will be manufacturing [5] or be easily modified so that new products could be manufactured and can produce low volume products or customizable products at a low cost [2,5,17,20,26,27]. In other words, if there is a new product range, there is no need to change or reconfigure the whole production line [27]. Other than that, the production line must have the ability to adapt to the current situation of the production process. For example, if there is a breakdown, the controller can reroute the workpiece in progress [5] or manufacture another batch of the product.

From the survey in [42], 74% chose the smart product as the key element of Industry 4.0. Smart products are manufactured in smart factories. Products will be designed in a way that it could be manufactured using common manufacturing processes. Products are customizable, modular and individualized according to the customers' needs and desires rather than being produced in big batches. They are also able to be manufactured using the same base setup or layout of the machine [2]. This allows for low volume or one batch size production possible [4] whilst still making a profit [20]. Smart products will enable customers to be involved in the design, configuring, planning, production and recycling phase of a product [4,26,32,46]. With the help of virtualization, the customer could also have an insight of what the product will look like when it is finished as the end-to-end integration is implemented.

Other than that, energy efficiency is also the main topic of a smart factory [4]. Energy consumption will be carefully monitored and unused machines will be systematically shut down or booted up depending on production needs [5]. This involves a facility management system in which not only is the energy consumption of the machine is monitored but also the building itself, for example, the lighting and air conditioning of the building. Another key element of a smart factory is the safety of the personnel [4,27]. Human life must be a priority. Therefore, in a smart factory, sensors or monitoring devices will also monitor the presence of human beings and ensure their safety in the factory. For example, if a human is detected in the workplace of a robot, the robot will automatically stop. When the human is outside of harm's way, the robot will continue doing its previous job [27].

2.6.1 Controller

The controller of a system is very important in a smart factory of Industry 4.0. It is used to acquire signals, process the signal and control the system's output. A control system manages, commands, directs, or regulates the behaviour of various devices or systems using either an open loop or a closed loops mechanism. It can range from a simple home heating controller using a thermostat to large Industrial control systems which are used for controlling processes or machines. For continuously modulated control, a feedback controller is used to automatically control a process or operation. For sequential and combinational logic control, a programmable logic controller (PLC), a PC based controller or a microcontroller can be used. In an Industry 4.0 system, the control system will be decentralized and can be easily connected between controllers and to the Internet. Thus choosing a controller must consider the ability of it being able to exchange data with other devices using a certain protocol and its ability to connect to the Internet. Most controllers can easily communicate with each other but a reliable controller that can be used in an industrial environment and communicate through the Internet is a challenge. Traditional PLCs are mostly not equipped with the capability to directly connect to the Internet. PC based controllers can easily connect to the Internet but require a lot of software development and programming just to regulate a device. Microcontrollers on the other hand are usually not suitable for the industrial environment and also requires a lot of text programming. Therefore, PLC is the best option or better more, PC based controller with PLC function and interface. A solution needs to be figured out on how to get these PLC connected to the internet and this could be done using an interface software such as a SCADA software.

In Industry 4.0, control systems will be distributed across the entire production system and not as centralized as before [57]. Remote IO especially using wireless technology will be widely implemented. There could be multiple PLCs all talking to one another, each having its own program. From the software program, these PLCs will see each other just like remote IO, with no special set-up required to have everything in sync. Human Machine Interfaces (HMI) can also act as controllers, processing their programs locally rather than sending information to a PLC thus reducing the cycle times of processes. In an Industry 4.0 system, there is no central command centre as such. The IOs on the controller are processed locally, so there is no additional traffic on the network and each controller talks to each other via field bus or Industrial Ethernet protocol. The controller will also be modular in which it can be upgraded with additional hardware such as IO or software such as various communication protocols.

2.6.2 Sensors

In a smart factory, machines will be equipped with more complex sensing and actuating devices that could help the machine to make a decision [5,9]. Various sensors are used to gather information or data [22,46,50] that will then be analysed for various reasons or for digitalization to create a digital world. Advanced or intelligent sensors are installed throughout the factory, especially in the production line to continuously monitor the production line, energy level, human presence and product movement and quality [20,29]. From this, data could be collected and analysed for various reasons such as event triggering and warning. The whereabouts of products could also be carefully monitored [22]. For example, the machine itself will check whether it has produced or manufactured the right product and only then will it release the product to the next station. It will also control the supply of the material and the distribution or storage of the finished product. With these sensing capabilities, data will be collected and using the analysed data, the machine should be able to conduct self-improvement and self-diagnostics, for example, deciding itself the optimum time to carry out scheduled maintenance or preventive maintenance [26]. This will increase the efficiency of the machine and eliminate losses due to breakdowns and unnecessary maintenance [50]. Advanced sensors also have the capability to self-diagnose themselves and let the human know if they are working properly or not. This is, for example, the IO link sensors but at the moment the cost is still high.

2.6.3 Identification system

Identification system or technology is also important in Industry 4.0 to keep track of a product and to exchange data. The product itself will be labelled or given an ID by equipping it with identification sensors [9] such as RFID or barcodes and may also have sensors to collect data or monitor its health. The product may also have data storage devices to keep the data and may be equipped with some sort of communication device which allows systems or other things [20] to connect to it and gather or transmit data; in other words, it could always be identified and located at any time [9,25,39]. The specification of a product and the machine's process parameter are kept on ID tags, on a local server or even on a cloud storage accessible by the machine. Data can be imprinted directly in the ID tag [2] or the machine will then refer to a local database or connect to a cloud service to get the specification of the product and the parameters that need to be used to produce a product [17]. The product can communicate with a machine to tell the machine what to do [17,21,27,28,31,46]. This will provide information, for example, of the state of the product, its specification, parameter and many more so that the product could be tracked throughout the production line [2,4,21,22,25,26,31]. After the machine has done its part, it will send a message to the cloud on what it has done. This message will be conveyed to the next machine to continue the process.

If parameters of machines or specifications of products need to be changed, this could be done through the Internet. With this, a customer could monitor the production progress of the product and the manufacturer could obtain after sales data from the product [2,21,26,30,33]. With an efficient production system, last-minute changes can be made even when an order has been placed, provided that the product has not been manufactured [4,26,37]. This technology will also be used for aftermarket services such as for maintenance and collecting aftermarket data; in other words, various data of a product throughout its life cycle can be obtained [21,27,30,43]. RFID, near field communication (NFC) or barcodes, can be used for this matter. A barcode is cheap because it can be printed directly to a product, but not all things can be imprinted with a barcode and limited data can be encoded in a barcode. RFID technology is widely suggested as in [26,30,37,46,47]. RFID is a contactless sensor which uses an electromagnetic field to recognise a tag [37]. It comes in various shapes and sizes and it is very reliable. It is widely used and is very affordable in terms of cost. The advantage of using an RFID system is that it could store data. Furthermore, it does not need to be in direct view between the reader and the tag. In other words, it could be embedded in the product and does not need to be exposed. The barcode may be cheaper, but the amount of data that can be stored is limited, it cannot be imprinted on some products and it must be in sight of the scanner. More advanced RFID can also store data on the tag itself. NFC is a new technology that is currently being implemented widely day by day. It is an alternative that can be used other than RFID.

2.7 System Interfacing

The first step in creating a smart factory system is to collect data from various machines or devices that may run on a different platform or use a different kind of communication protocol. These data are then displayed on a user interface and used for monitoring. The next step is the ability to control certain functionalities of the production line or send commands to the system from the user interface. This can be used to trigger an event or start a process either automatically or by using the user interface.

Interfacing various systems is a complex task especially when it involves various systems from various manufacturers. Communication between machine to machine or human to machines can be established using discrete signals, binary codes, or data communication. Data communication is the best way to communicate as it reduces the complexity of hardwiring the system and more data can be exchanged involving the use of various protocols and Fieldbus connections (either conventional wired connection or wireless connection) or using the industrial Ethernet. The challenge is to integrate all of these various systems. Various communication protocols are used in the industry nowadays to communicate, such as Modbus, CANopen, ProfiNet, Device Net, EtherCAT, TCP/IP and ProfiBus [34,50,52].

A mechanism for data exchange must be selected for a machine to machine communication and for the human to machine communication. It is also best to select a mechanism that can be used to create the user interface of the system and link it to a database. The easiest way is to use a single software or application that can handle both communications.

2.7.1 SCADA Software

One of the methods that can be used to acquire, monitor, control and display data is by using the Supervisory Control and Data Acquisition (SCADA) technology [52,54,55]. This software is also used in an Industry 4.0 learning factory in Bochum University of Applied Science [34].

SCADA can be used to bridge or link various systems and devices using different kinds of protocols or platforms [55]. This is because SCADA could understand various protocols and therefore act as the interface between systems [59]. SCADA has since then been upgraded with Industry 4.0 requirements by adding functions such as remote access [55,56], scripting and animation. The SCADA software is an interactive software used for various functions mainly to create a functional user-friendly human-machine interface or to display data from devices such as a PLC [55]. Other than that, SCADA also has various functions such as an alarm function, event triggering, historian, trending, and recipe function and can also be used to create a script for various functions such as analysis. The SCADA software has made it effortless to create a user interface that is accessible through the Internet and connect to a database using SQL language for easy data management and analysis or for various functions such as data storage, ERP functions, and reports. This is a fast and affordable way to create a system that is ready for Industry 4.0.

2.7.2 LabVIEW

Another software that can be used is the LabVIEW software by National Instruments. LabVIEW is a system engineering design platform and development environment that can be used to interface various devices for data exchange and data processing, mainly used in a research lab and academia. It can run on various operating platforms such as Windows and Macintosh. It normally uses data acquisition and instrumental measurement for data processing, calculation, signal conditioning, data analysis and control. It can also be used to create a user interface for a system and consists of a variety of measurement instruments such as an oscilloscope or multimeter. LabVIEW applies a graphical programming method called G programming rather than text programming, making it user-friendly especially to those who do not have any text programming competencies.

Devices such as a microcontroller, PLC or even sensors can be connected to the software through various methods and connections such as using a USB or serial communication. Various data acquisition hardware can also be used to exchange data but it comes with a cost. Connecting to a device requires a driver. For this, only limited drivers are available, especially when connecting to a PLC even though it also supports various common protocols such as Modbus and OPC. It also requires a lot of programming or data management to connect an input or output from a PLC to be displayed or controlled on the user interface. LabVIEW is also a proprietary software and therefore the use of third-party devices are very limited. New versions of LabVIEW have been integrated with IoT functions for remote access. LabVIEW is a licensed software which means using it will involve some cost.

2.7.3 Visual Studio

The Visual Studio is a software from Microsoft. It is an integrated development environment (IDE) used to develop computer programs, websites, web apps, web services and mobile apps. It uses a text-based programme that supports various programming languages such as C, C++, JavaScript, HTML and XML rather than a graphical programming method which is appealing to some but not to others. It can support various operating platforms and come with a compiler and debugging tools.

It can be used to develop a graphical user interface and link various devices provided that there is a driver and that the application program interface (API) for the device is available. This creates a problem as not many manufacturers are willing to disclose their APIs. A good thing is that by using this software, a Web interface can be developed and connection to the cloud can be configured and deployed, giving remote access to users. It can also connect to a database, but the knowledge of SQL language is needed. The Visual Studio is a licenced software but a free version with limited functions is available.

2.7.4 Node-RED

Node-RED is an open-source interfacing system. It is a programming tool for wiring together hardware devices, application programming interfaces (API) and online services in new and interesting ways as part of the Internet of Things [61]. Node-RED is a flow-based development tool for visual programming developed originally by IBM which can be used to create JavaScript functions. It provides a browser-based editor that makes it easy to wire together flows using the wide range of nodes in the palette that can be deployed to its runtime in a single click. Elements of applications can be saved or shared for re-use. The runtime is built on Node.js. The flows created in Node-RED are stored using JavaScript Object Notation (JSON). Node-RED is one of the affordable solutions to develop an interface to connect various system and connect them to the Internet. It is also easy to use as it uses a flow programming language or a graphical programming language. As it is open-sourced, its application and resources are vast and growing by the day thus making it an easy and affordable solution.

2.8 Engineering Model

2.8.1 CONSENS

To complete the smart factory prototype, a principle solution model is needed as an overview of the whole system. This principle solution was used to develop the prototype. A specification technique called CONSENS or CONceptual design Specification technique for the ENgineering of complex Systems [15,16,40] was used to derive this principle solution. It was developed by the Heinz Nixdorf Institute, University of Paderborn and can be used to develop Mechatronic system models [40,57]. Figure 2.6 shows the aspect CONSENS which includes application scenarios, environment, requirements, shape, behaviour, active structure, and functions [16,58].

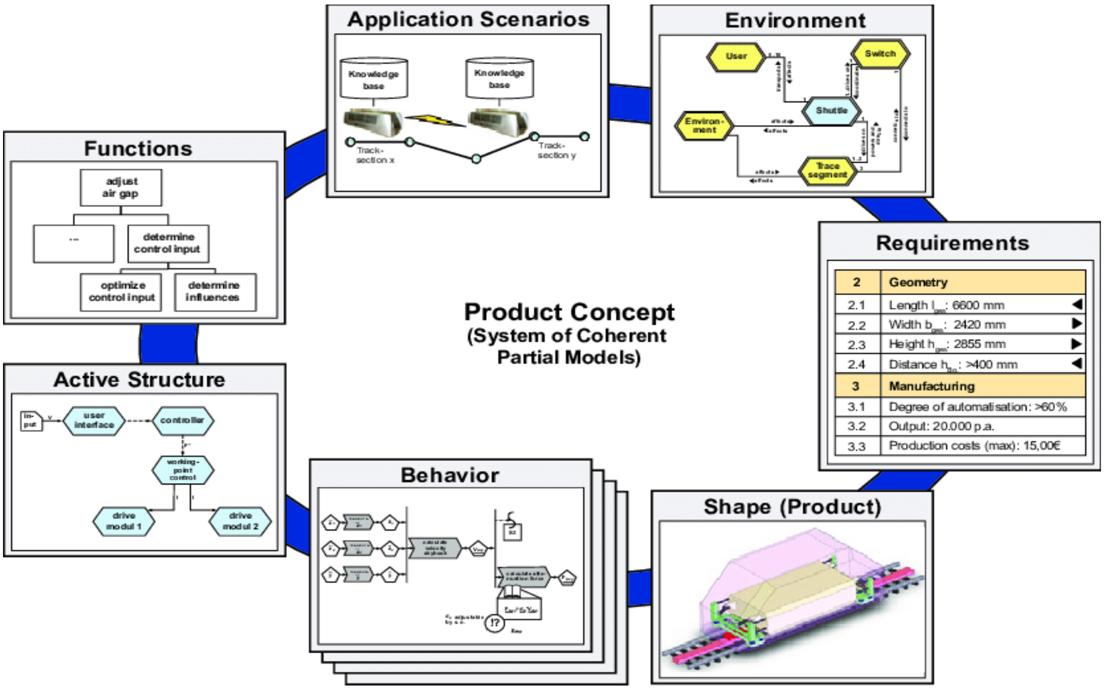

Figure 2.6: Aspects of CONSENS[15]

To develop a complex mechatronic system, an overview of the whole system is needed as mechatronics systems involve various disciplines such as mechanical, electric/electronic, and information technology. Therefore, the system needs to be divided into several aspects or partial models [15]. Each of these partial models will contain specific information concerning the system and this will give an overview of the whole system without any redundancies [40].

The environment model describes the environment of the system that is developed in the context of how the surrounding influences the system or how the system influences the surrounding [62–64]. The application scenarios model describes the situation and how the system should react to it [57,58]. The requirements model presents an organized collection of requirements that need to be fulfilled during an operation. This includes the specification, internal demands and customer demands [57,58]. The functions model describes the hierarchical subdivision of the functionality. The main function has to be split up into partial functions to define the features of all the subsystems [57,58]. The active structure model shows the system elements, their attributes as well as the relation of the system elements. It shows informative, energetic and material interactions between all parts of the system to get a better understanding of the functionality [62–64]. The behaviour model defines the states of the system and the state transitions. The state transitions describe the reactive behaviour of the system towards incoming events [62,63]. The shape model shows the shape of the product or the system using 3D modelling [57,58].

2.8.2 RAMI 4.0

The Reference Architecture Model Industrie (RAMI) 4.0 is a framework that shows a three-dimensional map on how to approach the issue of Industry 4.0 in a structured manner. RAMI 4.0 ensures that all participants involved in Industry 4.0 discussions understand each other. It enables standards to be identified in order to determine whether there is a need for additions and amendments. RAMI 4.0 is service-oriented architecture. It combines all elements and IT components in a layer and life cycle model. It also breaks down complex processes into easy-to-grasp packages, including data privacy and IT security [65]. RAMI 4.0 was developed by the German Electrical and Electronic Manufacturers' Association (ZVEI) to support Industry 4.0 initiatives, which are gaining broad acceptance throughout the world [66]. RAMI 4.0 is a three-dimensional layer model that compares the life cycles of products, factories, machinery or orders with the hierarchy levels of Industry 4.0. The model divides existing standards into manageable parts. The objective is to provide a clear structure for the interdisciplinary topic of Industry 4.0 [65].

For SMI companies, RAMI 4.0 provides a tool that enables and supports them in introducing and implementing non-manufacturer-specific solutions. In addition to standards, application scenarios and solutions are to be taken into account in the future. The model recommends the associated standards for each application scenario and solution. This can only be achieved if SMI actively participates in this process, because, as both users and providers of Industry 4.0 solutions, they have the expert knowledge required. This is the only way to ensure acceptance among users and providers [65]. Figure 2.7 shows the RAMI 4.0 model.

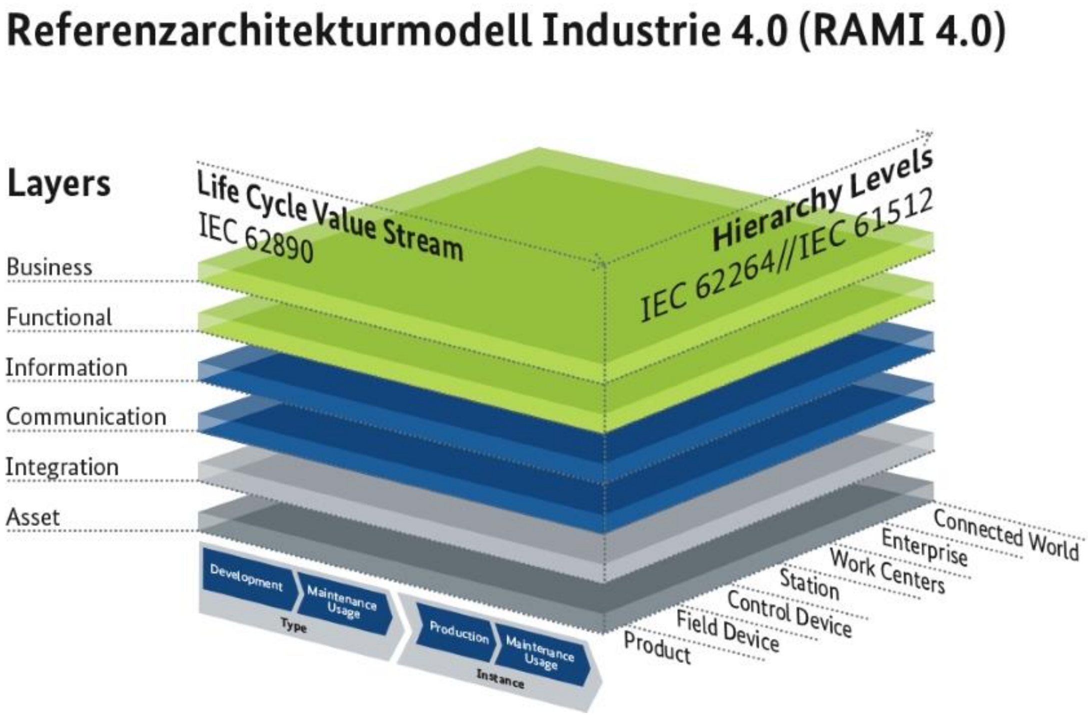

Figure 2.7: The RAMI 4.0 Model [66]

2.9 Industry 4.0 Toolbox

The Industry 4.0 toolbox is a toolbox developed by VDMA as a guide for small-medium industries (SMI) to evaluate the Industry 4.0 application level of their product or their production system. The VDMA toolbox was created to guide the SMI in developing or implementing Industry 4.0 in their organization. It was developed in cooperation with Technical University Darmstadt and Karlsruhe Institute of Technology (KIT) with the participation from several companies such as ARBURG GmbH & Co KG, HAWE Hydraulik SE, SCHUNK GmbH & Co. KG and SMS group [36].

Figure 2.8 shows the toolbox for evaluating the application level for production. In this toolbox, there are six aspects that are evaluated. The six aspects are data processing in the production line, machine to machine (M2M) communication, company-wide network with production, ICT infrastructure in production, man-machine interfaces, and efficiency with small batches. Each of these aspects is divided into five levels with level 0 as a non-Industry 4.0 system and level 4 as the highest level of Industry 4.0.

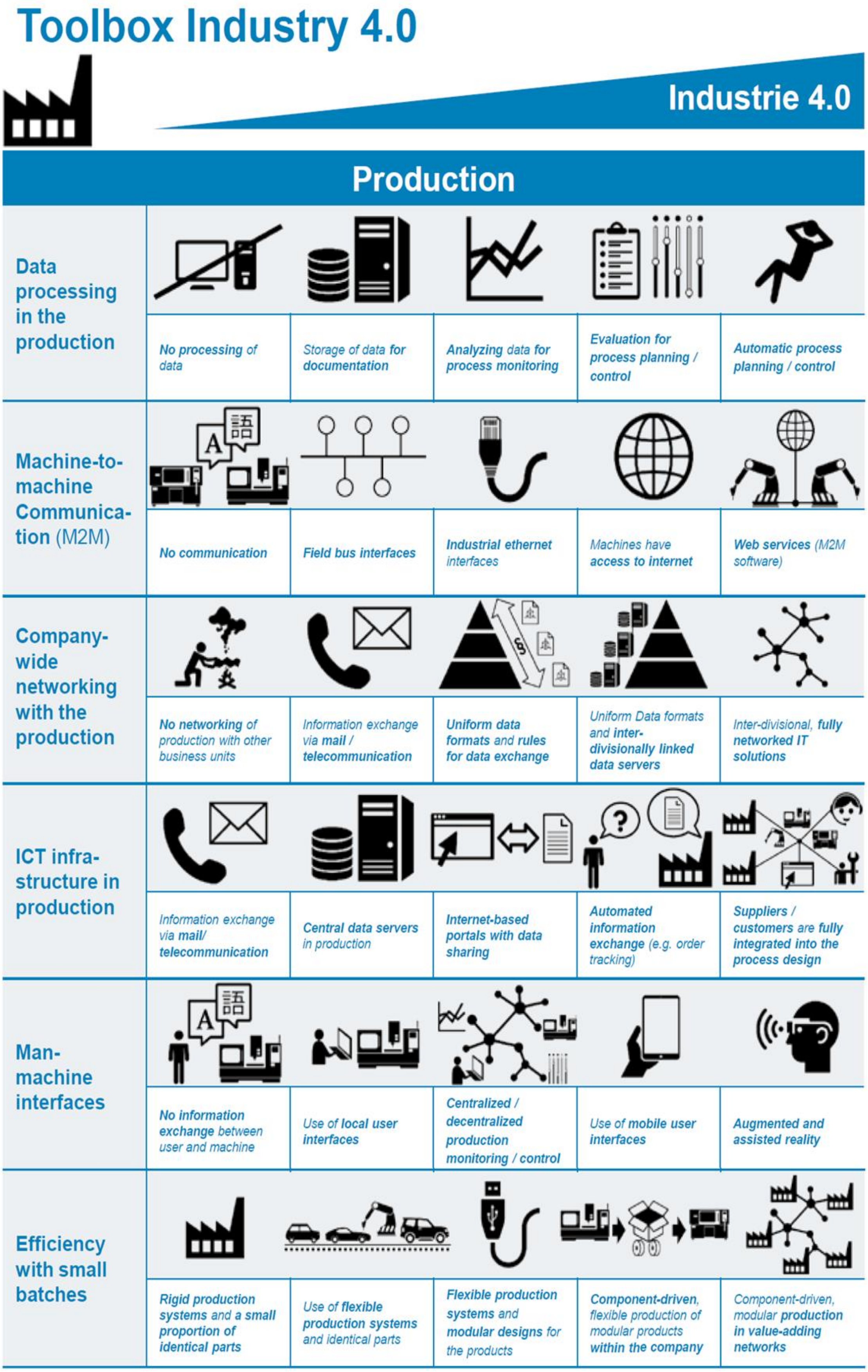

Figure 2.8: Industry 4.0 toolbox by VDMA [36]

2.10 Related work

There are a few related works that have been done by various companies or organizations concerning Industry 4.0. These works are focused on developing a prototype of smart factories.

Acatech or the National Academy of Science and Engineering represent the interests of the German scientific and technological communities and is a non-profit organization. Acatech supports policymakers and society by providing technical evaluations and recommendations. Acatech also supports knowledge transfer between science and the industry [20]. In Industry 4.0, Acatech carried out technical evaluations and recommendations on the topic. In 2010, Acatech initiated a research project on cyber-physical systems [28]. They also coordinated an Industrie 4.0 Working Group that formulated and produced a report on recommendations for implementing the strategic initiative of Industry 4.0 in 2013.

The next organization is the German Research Center for Artificial Intelligence (DFKI). It is a leading research centre in the field of innovative commercial software technology using AI. DFKI develops product functions, prototypes and patentable solutions in the field of information and communication technology. For Industry 4.0, DFKI is a partner of the Industry-Science Research Alliance advisory group. It works with policymakers in order to design and practically implement a joint project that will benefit society. For a few years, DFKI together with leading plant manufacturers has operated the world's first so-called "smart factory" as a living lab that acts as a reference of architecture for Industry 4.0 The project is called "RES-COM" [20,28].

Another organization is the Fraunhofer-Gesellschaft or Fraunhofer Society. It comprises of 67 institutes located around Germany. Each of the institutes focuses on different fields of applied science. It undertakes applied research that drives economic development and serves the wider benefit of society for customers and contractual partners in the industry, the service sector and public administration. It has helped to shape the Industry 4.0 project since 2011 by participating in the Industry-Science Research Alliance [20]. Since 2012, they have been working with industry partners in the area of highly flexible, self-organized capacity management as part of the publicly funded "KapaflexCy" INDUSTRIE 4.0 lead project. They have also developed new applications and business models for Industry 4.0 [28].

it's OWL (Intelligent Technical Systems OstWestfalenLippe) is a science and industry technology network with an alliance of 174 businesses, universities and other partners that carry out researches in this area. it's OWL is a network that intends to set international standards in the field of intelligent technical systems. Intelligent products and production systems are currently being developed in 45 projects. it's OWL is currently the largest INDUSTRIE 4.0 project. INDUSTRIE 4.0 solutions are currently being developed with a budget of around EUR 100 million [25,28].

Another project that was referred to in developing this prototype is one that was done by Bochum University of Applied Science as explained in [34]. Here, an Industry 4.0 Learning factory was invented at the campus Velbert/Heiligenhaus (CVH) of the Bochum University of Applied Sciences, where the processes at the shop floor level are integrated to the top floor level and vice-versa to generate a maximum of transparency. The Learning factory comprises of a holistic model of a company, from the Enterprise Resource Planning (ERP) level (Top Floor) to the Field Level (Shop Floor). Here, Systems Applications and Products in Data Processing (SAP) as the ERP System is installed. SCADA, Manufacturing Executing System (MES) and Energy Monitoring also the PLC, HMI and the appropriate Engineering Tools are from Schneider Electric. Simulation and offline programming tool for the robot are from Festo. A Festo mechatronic and pneumatic transfer system builds the material flow system for the workpieces in collaboration with the robot. The transport belt of the transfer system is driven by a variable speed drive. The components are interacting by the most common industrial communication standards including Modbus, ProfiBus and CANopen as field busses, Modbus-TCP, ProfiNet and OPC as state of the art Industrial Ethernet systems. Some of the concepts that were used in this system are implemented in the prototype developed in this research.

There are many organizations working on the development of Industry 4.0 systems. As can be summarized above, many research institutes are developing prototypes such as the smart factory model to help others understand Industry 4.0 better.

2.11 Literature Review Summary

Industry 4.0 or the fourth industrial revolution is the future of the Industry. This revolution creates new opportunity yet it is challenging in some way. The first gap that needs to be resolved is to establish the fundamental core of Industry 4.0. As stated in various literature, there are nine to eleven pillars of Industry 4.0. These pillars are technologies that support Industry 4.0. It can either be applied individually or in the combination of either of the eleven pillars. It can also be concluded, that the main fundamental of Industry 4.0 is the Cyber Physical System. This involves the digitalization of physical systems, data exchange between devices and connection to the Internet. It also involves the integration of ICT components into a system. Other than that, one of the goals of Industry 4.0 is to create and individualize product or batch size one. This involves mass customization in a production line. Among the application of Industry 4.0 are smart factory, smart city, smart product, smart building and smart transportation system. In this research, the focus is to develop one of the application of Industry 4.0 which is the smart factory. It is to equip the fundamental core of Industry 4.0 which is digitalization, data exchange, connection to the Internet, integration with ICT, and mass customization.

Industry 4.0 is driven by several factors. Among others is the Internet that has influenced humans' lifestyle and way of work. Other driving factors are technological advancement at an affordable cost, global economic order, new knowledge and skills discovery, a better supply chain, labour movement, and changes in consumers buying habits. With all of these driving forces, it seems that this revolution is unstoppable and therefore, in order to sustain, this revolution must be taken seriously. In order to successfully implement Industry 4.0, the concept of Industry 4.0 must be first understood. The second gap is how to develop an Industry 4.0 system that can be used to show the concept of Industry 4.0. This includes how to integrate the various system and this must be done at an affordable cost using currently available components to expedite the implementation of Industry 4.0. Many research carried out on this topic is concerning creating a smart factory prototype for example by it's OWL, DFKI, Bochum University of Applied Science, and Fraunhofer-Gesellschaft.

The third gap is how to create an interface to interconnect various system and also act as a human machine interface so that people can interact with the system either locally or through the Internet. In term of interface, there are many options that can be used. This depends on the budget, level of knowledge and the availability of software. LabVIEW, SCADA, and Visual Studio are licensed software that can be used. An open source option is using Node-RED. LabVIEW, SCADA and Node-RED use a graphical based programming language while Visual Studio uses a text based programming language. The choosing of the suitable interface software depends on the knowledge one poses, type of controller used and if the license for certain software is available. Using an open source software may save a lot of money but in term of reliability and support, it may lack. Using a SCADA system makes it easier to integrate and connect various system and devices to exchange data especially when using a PLC as the controller rather than using LabVIEW and Visual Studio. It can also act as a gateway to connect to the internet and connect to various ICT components such as to a database. A SCADA software can also be used to develop the user interface. The downfall is in term of connectivity in which the number of users that can be connected simultaneously depends on the number the license subscription. As this research is using a PLC, and the licence for a SCADA software is already forehand, the SCADA software was used.

A smart factory is a connected factory that is highly automated. The next gap is to set the basis of a smart factory in the context of Industry 4.0 that can be implemented directly without a big budget. First of all, the smart factory must be able to produce a customized or modular product. The controller used in this system is a PC based controller that uses PLC function and implementation method. This is chosen as it is reliable, uses industrial Ethernet protocol, and can be programmed using various PLC languages. It will also implement a decentralized control concept. As for the detection system, using an RFID system is better than using a barcode system or a magnetic strip system. This is because RFID does not need the tag to be in direct sight of the reader. Data can also be written on to the tag. Other components include a digitalize user interface to display data and control the system either locally or through the Internet.

Next is to choose the right model to describe the whole system. Two models that were discussed which are CONSENS and RAMI 4.0. CONSENS consist of several parts and only the active structure is used. The CONSENS model was used as it showed all the elements of the whole system and how they are connected with each other. It can also show the flow of material, energy and information which is very important to Industry 4.0. Lastly, in term of evaluation, the functionality test was carried out to show that the system can function well, can communicate and that the digitalization process is done correctly. The VDMA toolbox is used as it is specifically used to SMI which is suitable for an education trainer and as said, most Industries in Malaysia are SMIs.

CHAPTER 3

METHODOLOGY

This chapter discusses how this research was carried out. The main goal of this research was to develop an Industry 4.0 prototype by upgrading an existing system and using currently available components. To do this, first of all, information on the fundamentals of Industry 4.0 including its components were gathered and reviewed. Then, the development of the smart factory was carried out. This included determining the product, the production layout, the integration and interfacing of the system, the network interconnection and the system's user interface. After the development of the system was carried out, the system was evaluated to see the functionality of the system and the Industry 4.0 application level of the upgraded system

3.1 Research Strategy

This research used the concept of applied research. In general, applied research is a methodology used to solve a specific, practical problem of an individual or group [67]. This involved solving a problem or applying certain fundamentals using known theories or concept or principles. The aim of this research was to use a broad base and unspecific available knowledge and fundamentals concerning Industry 4.0 to develop a smart factory prototype in the context of Industry 4.0 by upgrading an existing system that can be used as a training aid. This is to solve the problem of the lack of affordable training system that can be used immediately to create awareness on Industry 4.0 and to show the concept of Industry 4.0. Also to solve the problem of integrating various existing systems to work with each other. The fundamental methodology of this research was to apply knowledge, concept and principles of

Industry 4.0 from various available sources to build a working model based on the Industry 4.0 requirement using currently available components such as PLC, RFID, and network components and integrating them together to build a fully working system. This was to show that it was possible to upgrade an existing system using common components and that it is cheaper than buying a new system [46].

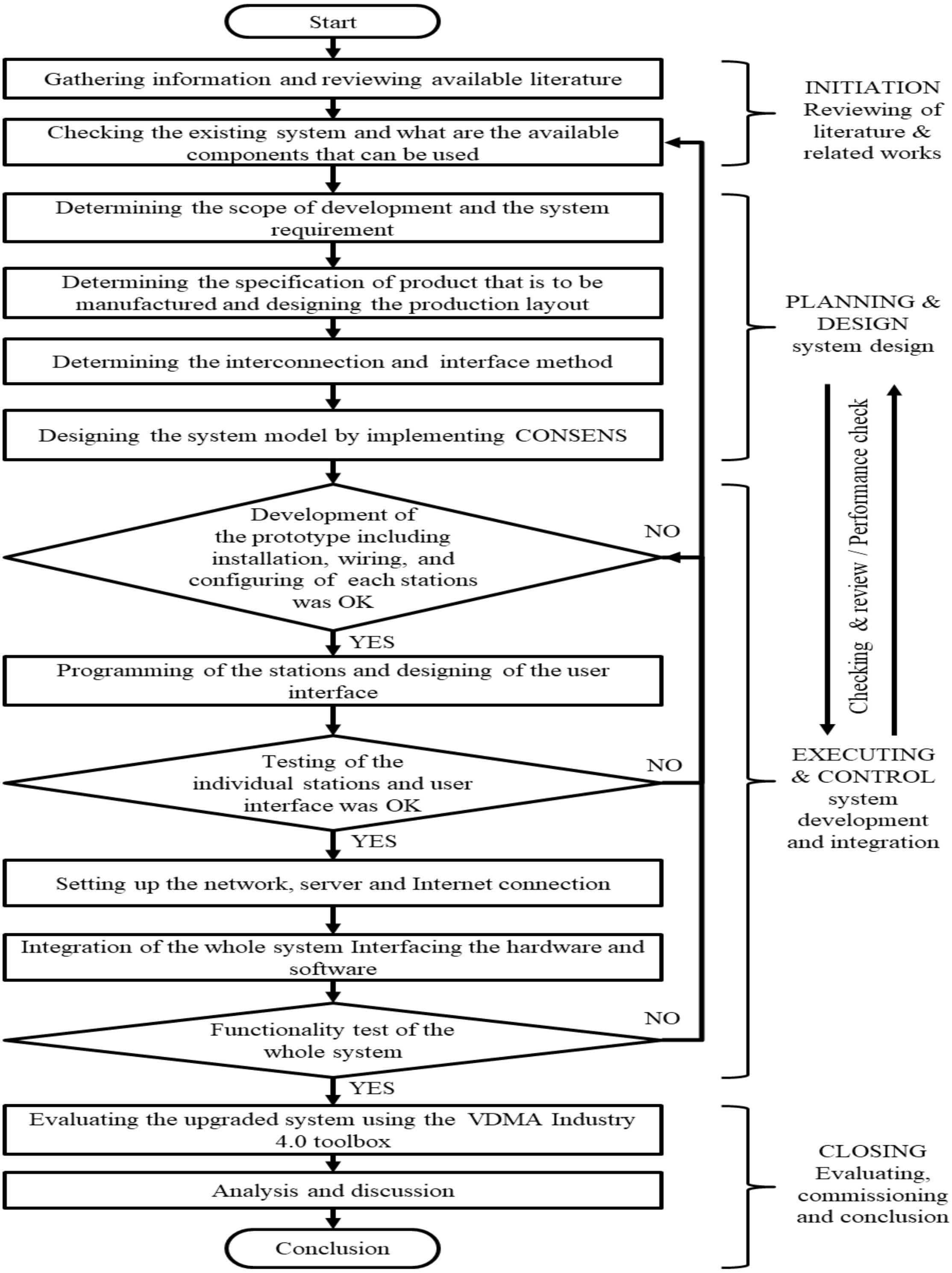

Figure 3.1: Development flow of the system

Figure 3.1 shows the development procedure of the whole system. After conducting a review of available literature and gathering information, the first activity was to evaluate the existing system and see what available components were on hand. This was to determine how the existing system can be upgraded, its technical requirements, how to interface it and what types of products can be assembled using this system. For this, all the requirements that the prototype needs to achieve are listed. The VDMA Industry 4.0 toolbox was also used to evaluate existing stations to see which of the six aspects can be upgraded. Based on the evaluation, the next step was to design the production layout and determine the process that needed to be carried out to assemble the product. For this, a conceptual design was drafted. From this conceptual design, a more concrete design or engineering model was derived using CONSENS. The CONSENS's active structure model shows the overall system components, the material flow, the energy flow and the information flow of the whole system. It shows the overview of the system and how the elements in the system interconnect with one another. The information flow is very important to make sure the exchange of data is done correctly.

From the CONSENS model, the development was divided into hardware development and software development. The hardware development involved configuring the layouts of the production line and all its components, while the software development focused on programming, data exchange and the development of the user interface. The hardware development of the system starts with the installation, wiring, configuring and programming of the stations. This included modifying the existing system's layout into an upgraded version that was able to assemble the intended product. Parallel to hardware development, software development is also started. In this aspect, work on interfacing of the whole system and the development of a graphical user interface using the SCADA software was carried out. Then, the local network and server were set up. This included setting up the IP address for each device. Lastly was the integration of the whole system to make the system work with each other. When the system was completed, tests were carried out to check the functionality of the hardware and the user interface including its connection to the Internet. Lastly, an evaluation of the system was carried out in terms of application level.

3.2 Design Methodology

This smart factory prototype was a Mechatronic system. Therefore, to develop the prototype, the design methodology VDI 2206 was used [59,60]. Figure 3.2 shows the V model. First of all, the requirements of the system were determined. The proposed requirements are elements that are needed to make the prototype Industry 4.0 compliant or that can show the concept of Industry 4.0. The six aspects of the VDMA Industry 4.0 toolbox were also referred and used to evaluate the existing station in determining the requirements. From these requirements and the evaluation of the existing system, the design overview of the system was derived. The design focused on the production layout, production process and the interface method. Most of this is described in the CONSENS model. With the overview model of the whole system, the domain-specific components were designed.

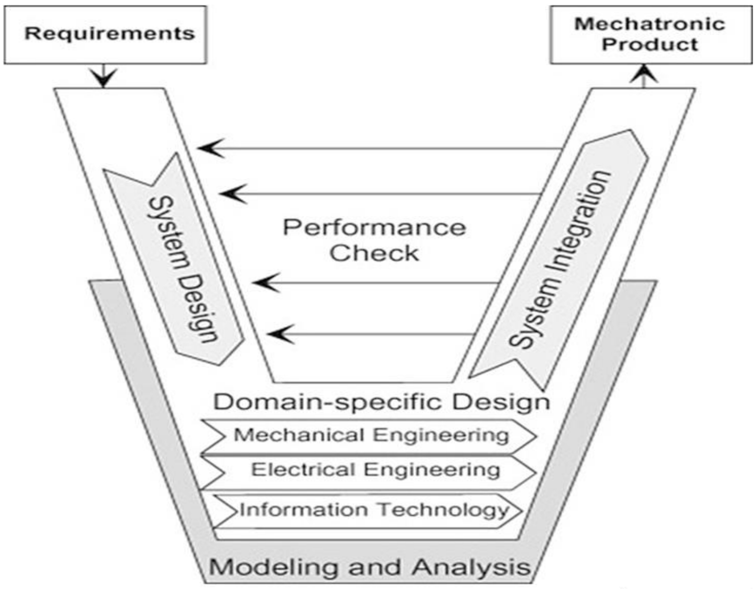

Figure 3.2: Design methodology according to VDI 2206 [59,60]

The domain-specific components included the mechanical domain, the electric and electronic domain including the control system domain, and the information technology domain. The mechanical domain consisted of mechanical systems and the movement mechanism such as the pneumatic components, conveyors, and structures. The electrical and electronic domain included the power distribution system, various sensors, electrical actuators, and lights. The control system domain consisted of Programmable Logic Controllers used to control the whole system and program the sequence of the production process. Lastly was the information technology domain which involved the networking of the whole system, data exchange method, the user interface and database connection. In this phase, each domain was selected or designed according to the previously set requirement taking into account what are the components and devices which are available on hand. Existing parts were used as often as possible and only if a component was not available and the system could not continue without it that a new component was bought. There were also parts that were fabricated using 3D printers to save cost. Various types of sensors were used for different kinds of detection. During this period, suitable components were tested and analysed to determine whether the suitable components were selected.

After the domain-specific design was done, the next process was the integration of the whole system by combining each specific domain to create the Mechatronic product, or in this case, the smart factory prototype. Integration involved connecting and configuring all the components of the mechanical and electric/electronic domain parts and programming them together so that the whole system works in synch with one another. During this process, the performance of the system was constantly checked with the requirements that need to fulfil and if there was any problem or incompatibility, the design of the system was reviewed and redesigned to find a suitable solution [64]. This research used an existing educational trainer called the Modular Production System by Festo. The objective was to upgrade the system and turn it into an Industry 4.0 system.

3.2.1 System Requirement

The first aspect of designing a mechatronic system is to determine the requirement that a system must achieve. The requirements for this project were based on Industry 4.0 elements that can be implemented or upgraded from the existing system along with currently available components. The main goal is to show the fundamental concept of Industry 4.0 such as digitalization of a physical system, data exchange between devices, connection to the Internet, integration of ICT components into a system and to create an individualized product.

The first requirement that was set was that the system must be able to produce a modular product in which consumers can configure the product they want to buy. This is to show the concept of mass customization. The second requirement is to create a decentralize control concept in which each station will have its own controller. The third requirement is to digitalize the system as much as possible by digitalizing the IO signals and displaying them on a digitalized user interface. Then, the system must be interconnected within a local area network to exchange data with each other mainly using industrial Ethernet technology or any other field bus connection. Another requirement was to use a single interface to manage the data exchange between various systems. Next is to create a user interface that can be used for local access or remote access and to visually display the IO statuses of the system on a digitalized display. This involves connecting the system to the Internet for remote access. For the ICT function, the system must be able to connect to a database especially for the ordering system and also to save data on a storage. The additional requirement included the integration of RFID in the system.

3.2.2 Product

Before designing the production layout, the design and specification of the product that was to be assembled must first be determined. Therefore, the first step was to determine the product that will be manufactured. In this research, the original workpiece of the trainer was used. The original product consisted of two parts. The first part was a round-shaped cylinder case and the second part was a cap which was assembled on the cylinder case. Figure 3.3 shows the first part which is the case. As can be seen in the figure, the case came in two colours which were black and red. Figure 3.4 shows the second part of the product which is the cap. The cap also came in two colours, which are black and red. For this prototype, the user can mix and match the different colour of case and cap to create several variants of the end product.

Figure 3.3: The first part of the product called the case

Figure 3.4: The second part of the product called the cap

3.2.3 Mechanical Domain

The mechanical domain of the system consists of the existing trainer including various electro-pneumatic system, mechanical structures, electro-mechanical parts and others. This trainer consisted of several mini production stations, each with its own processes, but only three were used in this research. These three trainers were combined to create a functioning production line. To be able to assemble the required product, two of the three stations must be heavily modified from the existing one.

The first station was originally the handling station, which can be seen in Figure 3.5. A few modifications had to be made as this station did not have a module that could store and dispense two different colours of workpieces. There were also components that were not used and therefore must be removed. The station consisted of a pneumatic linear actuator used for the pick-and-place operation.

Figure 3.5: The handling station [69]

The second station was heavily modified from the pick-and-place station. This station needed to be able to dispense the infill, dispense two different colours of caps, and pick and place the cap on to the case. Figure 3.6 shows the original station. The original system consisted of a conveyor for transporting a product and a pick-and-place module with vacuum suction for pick-and-place operation. In this station, most of the components were removed and replaced with other components so that it could do the intended process. Among others, the pick-and-place module was removed and replaced with a gantry system because the original one can only stop accurately at two points. Two cap dispensing modules also needed to be added for the cap.

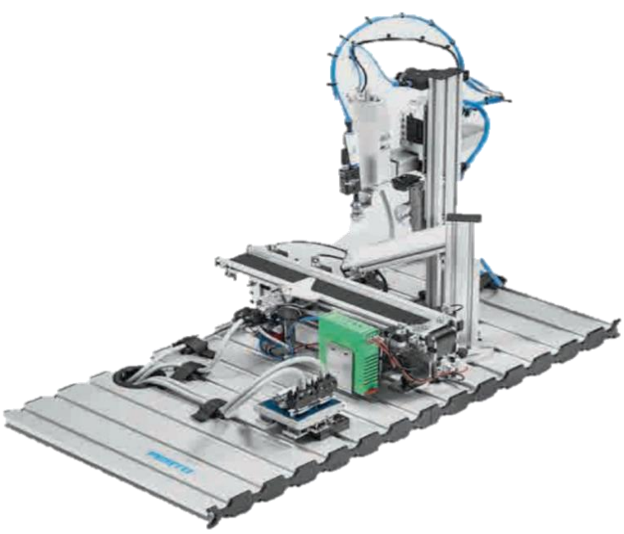

Figure 3.6: The pick-and-place station [70]

The third station was an original sorting station with minimal modification. The station can be seen in Figure 3.7. It consisted of a conveyor, three slides and two gates to separate the product. It also had various sensors to detect height and colour.

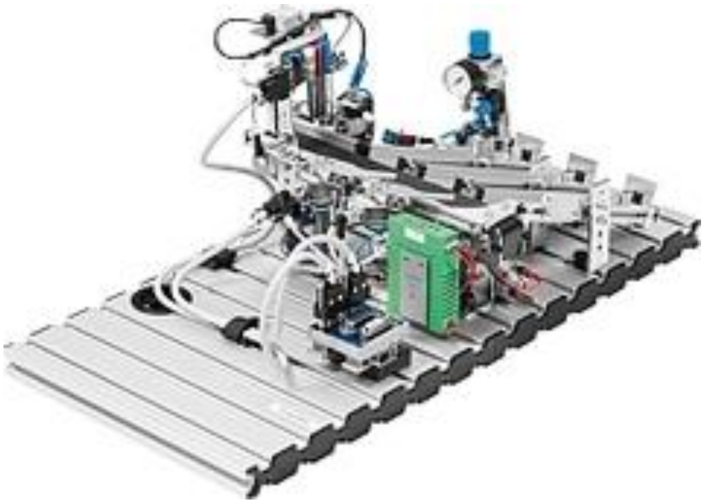

Figure 3.7: The sorting station [71]

Other hardware included a digital power meter which was used to monitor the voltage, current, and power for display. This digital power meter used a Modbus RS485 protocol, thus a converter was needed to convert the RS485 data to an Ethernet connection.

3.2.4 Electrical and Electronic Domain

For the electrical and electronic domain, it consists of the power distribution system, electronic components and the controller used in this system. The main power source is using a 24Volt DC system. This is supplied using an AC to DC power supply. DC motors are also used to move the conveyour belts. Among the electronic components in this system are various digital sensor, analogue sensors, various buttons, motor drivers, relays and signal lamp. All of these components are using a 24V DC supply.

For the controllers, a PC-based PLC was used instead of using a microcontroller or a PC. A PLC is an industry grade controller in comparison to a microcontroller like an Arduino and using a PC will involve a lot of software development. The PLC used was from Beckhoff which operated on Windows embedded CE 6. This was actually an embedded PC running on an ARM processor equipped with an Ethernet port for communication, but can be programmed using the five IEC 61131 standard PLC languages. This PLC supported various protocols such as real-time Ethernet, ADS TCP, Modbus TCP, TCP/IP, UDP/IP and EAP (EtherCAT Automation Protocol). The controller was a modular controller in which various digital and analogue input and output modules, as well as additional communication ports, can be attached as needed. Various IO modules were needed to interface components such as sensors and actuators to the controller. The IP address of the controller was set as a static IP which was important for communication. Figure 3.8 shows the controller used in this research. Using a modular system makes it easier to reconfigure the system later. This gives a degree of flexibility which is also important in a smart factory of Industry 4.0.

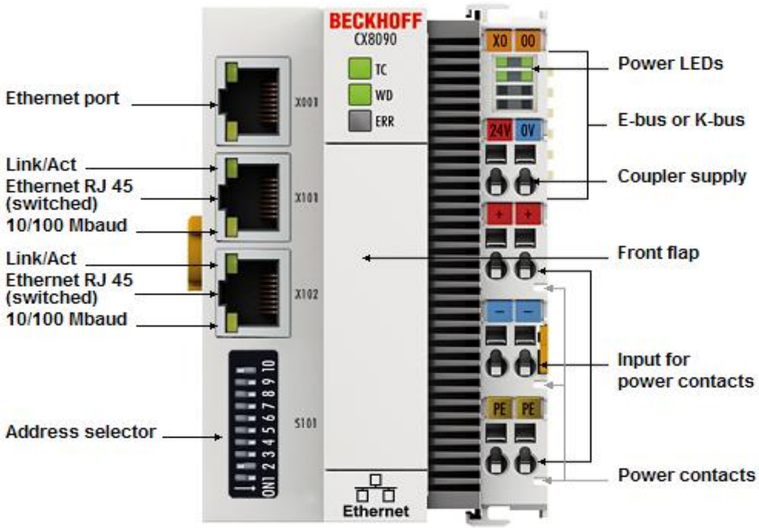

Figure 3.8: The CX8090 controller from Beckhoff [72]

3.2.5 Information and Communication Technology Domain

3.2.5.1 Software and Programming

To program the sequence of the production line, the TwinCat 2 software from Beckhoff was used. This software allows users to program the sequence of the system using any of the five IEC 61131 PLC languages. In this project, the programming of the controllers was mainly done using the Sequence Functional Chart (SFC) language which was easier to program and monitor as can be seen in

Appendix D, E and F. Other than that, the ladder diagram and structured text was also used.

SCADA software was used in favour of other software because it could easily integrate various systems or devices, provide remote access, link to a database and is easier to build a user interface. For the SCADA software, Indusoft Web Studio 8.0 was used. It is an affordable SCADA software with a collection of various automation tools and blocks to develop user interfaces, monitoring functions and embedded instrumentation solutions. This software also provides a solution to connect to the Internet/intranet for remote access. It can be connected to various databases and uses the SQL language. It can act as an interface as it consists of various drivers to connect to various types of controllers. For the database, the MSSQL Express 2017 database was used. This is free software that can be connected to the SCADA software. Microsoft SQL Server Management Studio 17 was used to manage and check the database.

3.2.5.2 Network and Server Setup

In order to create a smart factory, all stations must be interconnected and connected to the Internet. In this research, the Ethernet connection connected to a Local Area Network (LAN) was used as the main communication method. An eight-port Gbit Ethernet switch was used to interconnect the controllers. The LAN was managed by a TP-Link 300Mbps Wireless N router (TL-WR841N) with wireless connectivity and was connected to the Internet. Cat-7 Ethernet cables were used to connect the devices to ensure a fast and reliable connection.

On the same LAN, a server was connected. This server hosted the SCADA software and the database. To host the application, Internet Information Services (IIS) by Microsoft was used as the webserver. Here, a normal Intel processor laptop with a Wi-Fi connection running on Windows 10 connected to the router was used as the server.

3.2.5.3 Human Machine Interface

Human-machine interaction is very important. Thus, the interface must be designed carefully to be intuitive and provide functional visualization for control and monitoring [21]. For the visualization onsite, a touchscreen Human Machine Interface (HMI) was used to display the IO status of the system. It can also be used to control the basic functionality of the station. It could be used to display basic information such as the RFID tag number and the status of the production. The HMI was connected to the controller using the Ethernet connection. The layout of the HMI was designed using the PM Designer V2.1 software.

For remote access, the SCADA software was used to create the interface to monitor and control the system. It was used to link various data sources and display it on a screen. The advantages of using a graphical user interface are that it is possible to change the layout of the interface or add and remove various components to suit the production line rather than using a physical push button. The wiring is also less complex. This will give more flexibility.

3.3 Evaluation Methodology

After the prototype was developed, evaluations of the system must be carried out. First of all, a functionality test of the system was carried out. This is to test the functionality of the system. The proposed requirements of the prototype are also checked with the real prototype to see whether these requirements fulfilled or not. Next, the evaluation of the system using the Industry 4.0 toolbox provided by VDMA was done. There were some limitations to the evaluation. For example, full stress and endurance test were not carried out on the system.

3.3.1 Functionality Test

The first evaluation was the functionality test. This was to confirm the function of the whole system and to check whether it was functioning as intended. First of all, a list of behaviours or functions that the system can do and parameters that needed to be checked were determined. The actual operation of the system was cross-referenced to the operation flow charts of the system. Testing was done using a checklist.

The testing began with a dry test run. First of all, before testing the sequence of a system, the signal for each input and output (IO) was checked and confirmed. For this, an IO allocation list or IO address assignment list containing all the IO connections to the PLC was needed. A checklist was used to check all the IO as can be seen in Appendix A, B and C. The IOs were turned on and off for at least five times to see whether the signal was received and sent correctly by the PLC. This was done by checking the indicator on the PLC and the online monitoring feature on the PLC software. After all the IOs had been confirmed, the communication between PLCs was confirmed to make sure the PLCs could exchange data correctly. The next step was to check the functionality of various sub-systems in the prototype. For example, the dispensing of material, movement of conveyors, pick-and-place process, and others. This was to confirm the functionality of these sub-systems to ensure that the material can be processed and flow smoothly throughout the production line. This was also to confirm that the position of each component and sensors worked hand to hand.

Then, the link between the system and the SCADA software was checked. First of all, the connection status displayed on the SCADA software were monitored for any error. This was to ensure that the system can communicate with the SCADA software and to ensure the correct transfer of data and the correct link between the physical IO of the system, and the assigned tag in the SCADA software. The data link between components in the graphical user interface in the SCADA software and the PLC IOs and variables were also tested and confirmed. This was done by turning on an IO and checking whether the SCADA software received a signal. The local user interface or HMI connection was also tested and confirmed. This was done by checking the IO signal on the HMI in corresponding to the actual signal of the IO devices. Other than that, the link between the digital power meters was also checked and confirmed in which the data displayed on the digital power meter must be the same as what is displayed on the user interface. During this time, the connection link between the SCADA software and the MSSQL database on the server was also compared and confirmed. Data exchange to and from the database was checked using the Microsoft SQL Server Management Studio 17 so that the correct data was inserted or selected from various tables that were already created in the MSSQL database on the server. This is done by entering various parameter in the user interface and checking whether the correct data was inserted in the database. Other functions on the SCADA software were also checked, for example, the multi-role user login function, page change, alarm function, and event triggering. The digitalization of certain parameters was also compared and confirmed. This includes the reading of the air pressure which was checked with the analogue pressure gauge, the voltage which was checked using a multi-meter and the current which was using a clamp meter. Lastly, the RFID tags number that was red by the RFID reader and transferred to the PLC is confirmed. The RFID tag does not have the ID number imprinted on the tag. Therefore, each RFID tag number was read three times by the RFID reader to check for consistency. This is done by comparing the RFID tag number that was displayed in the PLC for each reading in which all three reading of the RFID tag number must be the same for the same tag.

The next step was to test the sequence of the system manually before running it on auto mode. The sequence was tested step by step from the beginning of the process until the end. After that, the system was tested on auto mode for each variant. The next step was to run a pilot test on the whole system. This was done to check the functionality and connectivity of the whole system by comparing the intended behaviour of the system with its real behaviour. Production of each variant of the product was carried out by the system before the system passed the commissioning process. This includes producing all the eight variant of the product back to back in one order and taking the cycle time of the whole process and comparing it to an existing system. Last but not least, the remote access of the system was tested. This was to make sure all the intended remote functions of the system can be done swiftly without any problem. The remote interface was based on the SCADA interface. Therefore, the same test was carried out, only that it was done remotely. This was to see if it still can communicate with the system remotely. With the entire test done, it was determined whether the system can fully function as intended.

3.3.2 Industry 4.0 Toolbox

The second evaluation was done using the Industry 4.0 toolbox developed by VDMA. The evaluation for this system was done using the production toolbox. In this evaluation, the application level of Industry 4.0 of the system was determined. Before beginning the upgrade, the existing system was evaluated using this toolbox. This was to see which aspect had the potential to be upgraded. After the system was upgraded, the evaluation was carried out once again. The determined level of Industry 4.0 of the new system was compared to the existing system to see its level before and after the upgrade was made. This was to show the ability to upgrade an existing system to a certain Industry 4.0 level [36].

This evaluation is a self-check evaluation that can be done either individually or in a group. In this research, the system was evaluated individually by comparing the criteria of each level for each aspect with the ability of the developed prototype to see whether the developed system had achieved this level or not. A concrete explanation must be presented to support the level that it has achieved. Based on the level it has achieved, a spider web graph was plotted to see the strength of the system. This also showed the aspect that needed or can still be improved. An evaluation was also carried out on the original MPS to see which level it currently was. Then, a comparison between the upgraded system with the normal system was carried out to see how much of an impact can be made by upgrading a system rather than changing the whole production line.

CHAPTER 4

PROTOTYPE DEVELOPMENT

This chapter explains the development of the smart factory prototype. The first principle solution for this smart factory was specified. Then, a prototype was developed by upgrading a modular production trainer. This chapter discusses the active structure model, the operation flow of the system, the production layout, the network setup and the interface that was developed.

4.1 Active Structure

The CONSENS specification technique was used to specify the solution for the smart factory. The active structure model shows the overall elements and connections between the system elements. Figure 4.1 shows the result which was the overall active structure model for the prototype. Figure 4.1 shows the elements in this system which were divided into two which were the internal system elements and external elements. The system element consisted of devices or elements that were directly connected to the system including the production stations, HMI, router, and server. The external elements were elements that may influence the system or that did not directly belong to the system such as the air compressor or the Internet.

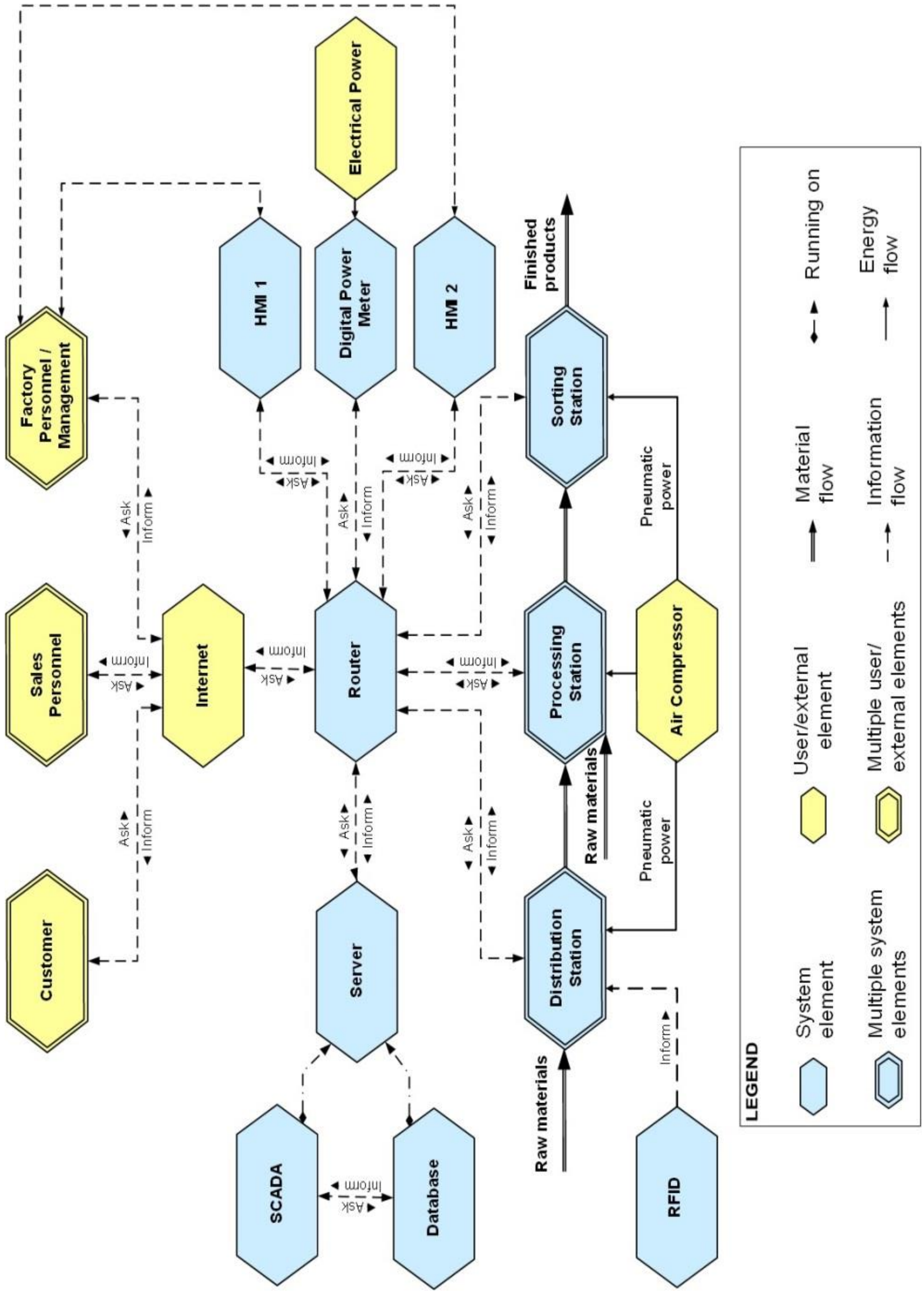

Figure 4.1: Active Structure for the overall production line

In the model, the flow of material, information, and energy were specified. The material flowed from the distribution station to the processing station and ended at the sorting station. Raw materials were supplied to the first and second stations to assemble the product. As for the information flow, the data exchange flowed between the system elements and the user or external elements. It also shows the Internet connection between the devices. Communication within the system was established using an Ethernet connection using various protocols such as TCP/IP protocol, Modbus TCP, and the Automation Device Specification (ADS) protocol. Exchange of data was done using a server-client system in which data was exchanged when there was a request. Each of the main devices such as the PLCs, HMIs, digital power meter, and the server had its own static IP managed and channelled by the router. Figure 4.1 also shows that the SCADA software and the database were running on the server. The router also acted as the gateway to the Internet for the whole system. This was important for security purposes as firewalls and filters could be set on the router. Remote access from different levels of users is possible through this gateway. With this, different levels of users could access the system locally or remotely according to their level of clearance.

Lastly was the energy flow. In this production system, the two main energy sources used were electrical power and pneumatic power. Electrical power was used to turn on all the electrical/electronic components including the controllers, sensors, server, router motors, and HMIs. Pneumatic power was used to actuate all the pneumatic components such as the pneumatic cylinders.

4.1.1 Active Structure for Distribution Station (Station 1)

Figure 4.2 shows the active structure for the distribution station or station 1. The main elements of this station included the PLC, the pick alpha module and the stack magazine module. Materials flowed from either one of the stack magazine modules as ordered by a customer. It was picked up by the pick alpha module that then transferred it to the RFID reader. After that, it was transferred to the second station for the next process.

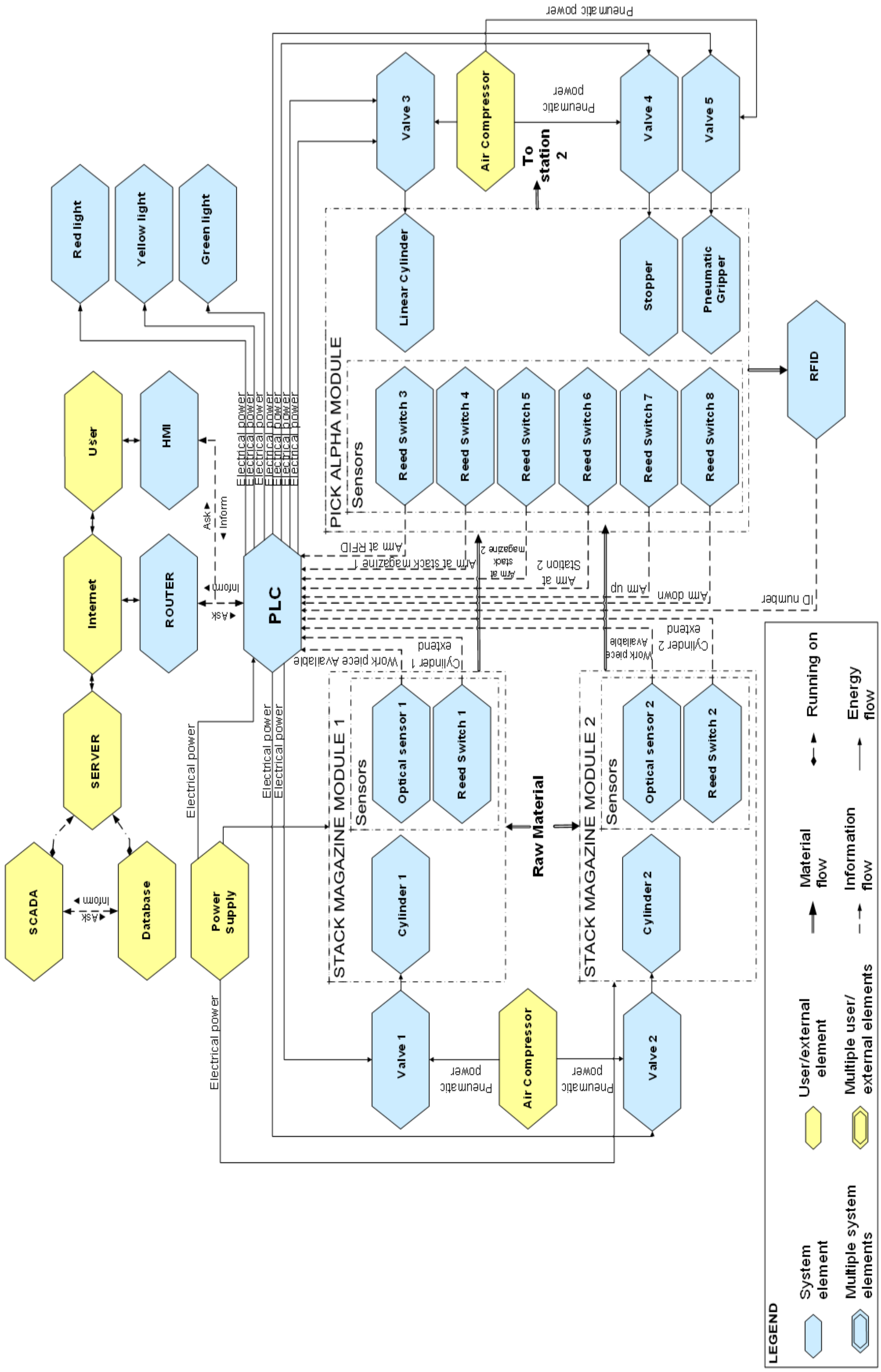

Figure 4.2: Active Structure for distribution (station 1)

The PLC took the role as the central command of the whole station. It acquired information or signals from various inputs such as sensors or command from the interface and processed these signals. According to the pre-programmed sequence, the instruction was given to the actuators to carry out the desired function. Sensors used in this system were mainly digitals sensors which gave a discrete digital signal except for an analogue pressure sensor used to read the pneumatic pressure. Information was constantly exchanged between the PLC, the HMI, the RFID reader and the software running on the server. The RFID reader was attached directly to the PLC using a serial connection using the RS232 protocol. The function of the RFID reader was to read ID tags on a product and send the data to the PLC. The PLC then sends the data to the SCADA software. The SCADA software constantly requested and sent information from and to the controller and displayed it on the screen. The database exchanged information with the SCADA software accordingly. All of this was done through the server. Users could interact directly using the HMI, the SCADA interface or through a web application.

For the energy flow, it used pneumatic and electrical power. Electrical power was used to turn on the PLC and sensors. The pneumatic power was used to move the pneumatic components which were controlled by pneumatic solenoid valves that were electrically powered.

4.1.2 Active Structure for Processing Station (Station 2)

Figure 4.3 shows the active structure of the processing station or station 2. The PLC remained as the main element of the system. Other system elements included the gantry module, the conveyor module, the filling module, and the cap dispenser module. For the material flow, this station received a workpiece in progress from the distribution station. The material was transported along the station by means of a conveyor module. Firstly, the unfinished product was transported to the processing point. The filling process was done here and it was then transported to the capping point. Here a gantry module would pick up a cap and place it on the workpiece in progress. After that, it was transferred to the next station.

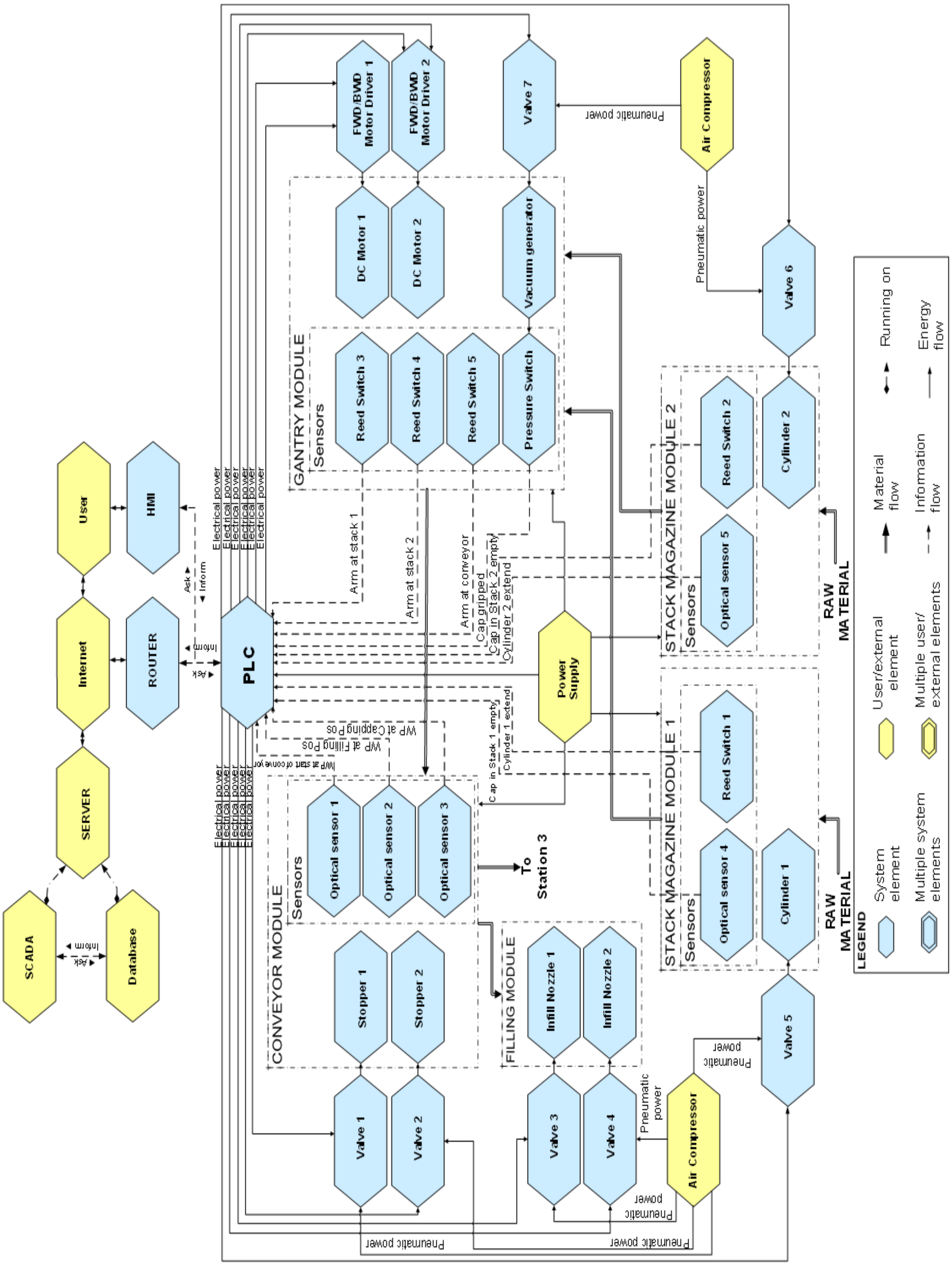

Figure 4.3: Active Structure for processing station (station 2)

Information flow was the same as in the first station mainly for signal processing and actuation. Here, electrical power was used to turn on a DC motor which was used to move a conveyor belt. This DC motor movement was regulated by a motor driver. The positioning of the arm on the gantry module was done using digital sensors which gave a signal to stop the movement when it detects an object or according to how it was programmed.

4.1.3 Active Structure for Sorting Station (Station 3)

Figure 4.4 shows the active structure for the third production station called the sorting station or station 3. This station inspects the finished product and then sorts it into slides. The information flow and energy flow is basically the same as the previous stations. The station receives the finished product from station 2 and transfers it to the checking point. If it passes inspection, it will then be transferred to the slides.

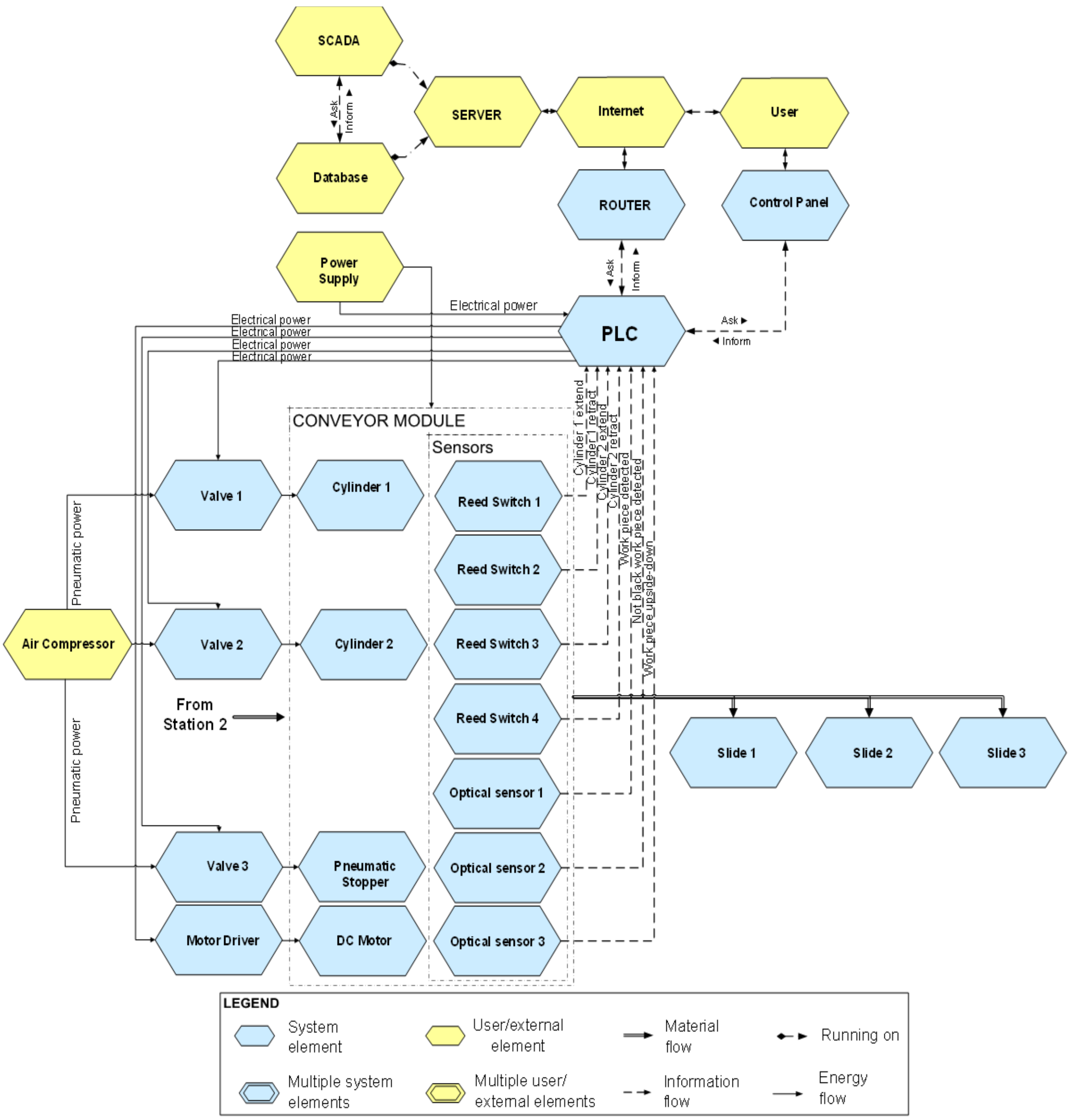

Figure 4.4: Active Structure for sorting station (station 3)

4.2 Overall Production Flow

This section explains how the prototype works. The main goal of this production system is to produce several product variants using the existing MPS workpiece consisting of two parts and a filling as stated in the previous chapter.

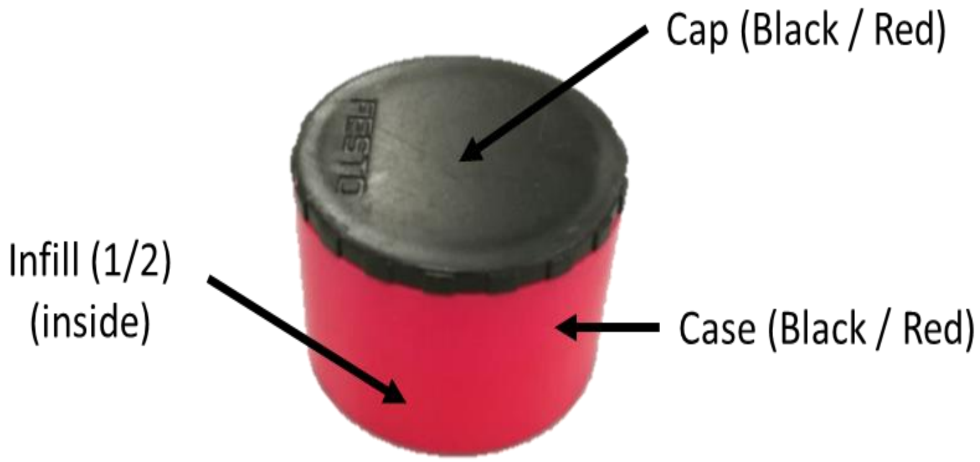

Figure 4.5: The fully assembled product

Figure 4.5 shows the fully assembled product. This product was assembled on the production line of this smart factory prototype. In Industry 4.0, the product will be customizable according to the requestor or be made modular so that people can mix and match what they want. A modular product is a way to create a variant without much effort by using standard parts across all variants [2]. In this research, a modular product concept was used to show the product variation or the wide variety of the product that can be ordered by a customer and assembled using the same production layout without any reprogramming of the system. Customers can pick from two different coloured cases, two different types of infills, and two different coloured caps. In this work, users can select from up to eight variants. Table 4.1 shows the list of variants of the product in which during the test run, all of these variants were managed to be produced either individually in a single order or all at once in one order. Figure 4.6 shows the different variants that are produced by the prototype.

Table 4.1: List of product variant

Variant	Case	Infill	Cap
Variant 1	Black	Infill 1	Black
Variant 2	Black	Infill 2	Black
Variant 3	Black	Infill 1	Red
Variant 4	Black	Infill 2	Red
Variant 5	Red	Infill 1	Red
Variant 6	Red	Infill 2	Red
Variant 7	Red	Infill 1	Black
Variant 8	Red	Infill 2	Black

Figure 4.6: Example of product variants

Other than its modular design, in general, a smart product should have the means to communicate with other devices or with human, able to exchange information or at least able to be identified. Therefore, to communicate, a smart product must have a communication device or system for example via WIFI, Bluetooth or radio signal. In this system, an RFID tag was attached to the product for identification. The product has its own RFID tag with an identification (ID) number and will tell the machine its ID. The machine will then cross-reference the ID given to a database. Specification of the product is stored on the database of a local server and is assigned to an RFID tag. RFID nowadays are getting cheaper and the tags come in different kinds of shapes and sizes. In this research, an RFID reader was put at the first station. The reader reads the RFID tag and stores it on the database for tracking purposes. Figure 4.7 shows the RFID tag that is attached to each case such as implemented in [17]. The RFID tag is the white coloured, round object in the case attached in the inside of the product.

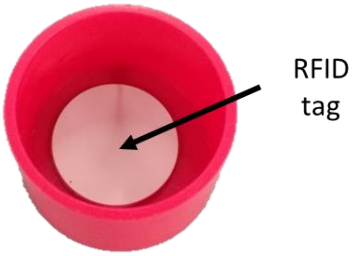

Figure 4.7: The RFID tag attached to the case

Figure 4.8 shows the overall production process of the system. The main process of this system was to dispense a case from a stack according to the ordered colour, read the RFID tag number and record it in the database, fill the case with either one of the fillings, close the case with either one of the available caps and lastly check and sort the product according to the order.

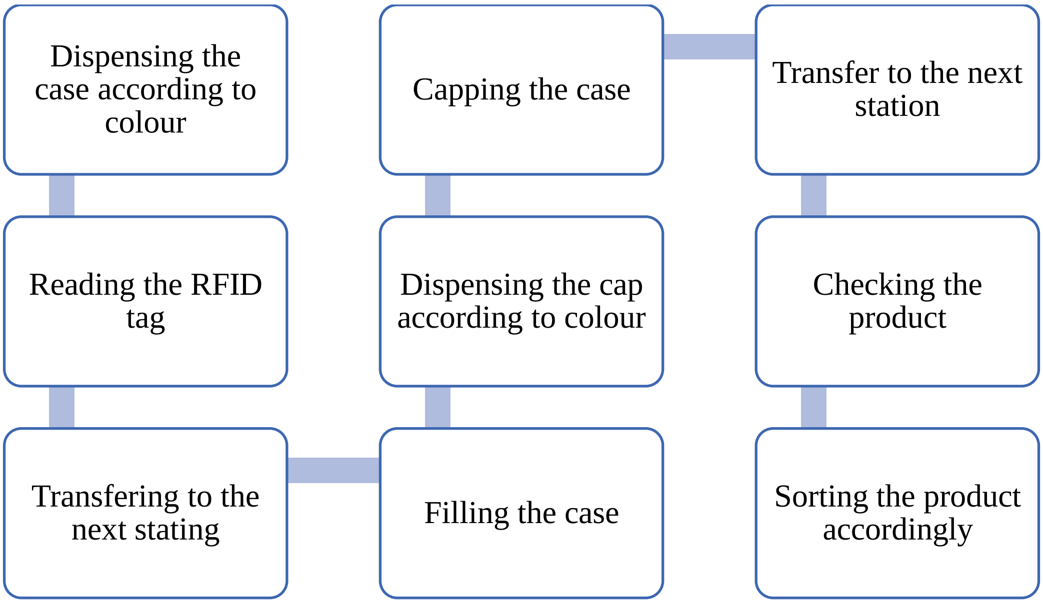

Figure 4.8: Production process overview

Figure 4.9 shows the overall operation flow. Firstly, the whole system must be initialized and running. The SCADA software acted as the backbone of the system. When the system is turned on, it will start to exchange data with the PLC or any device connected to it. It will start to acquire data or monitor various parameters such as the IO status, voltage, power and current. The production of a product starts when a customer places an order. Using an interface, the customer can select the colour of the case, the infill and the colour of the cap. The customer will select the quantity of each variant they want to order. The order is then placed and stored on a database.

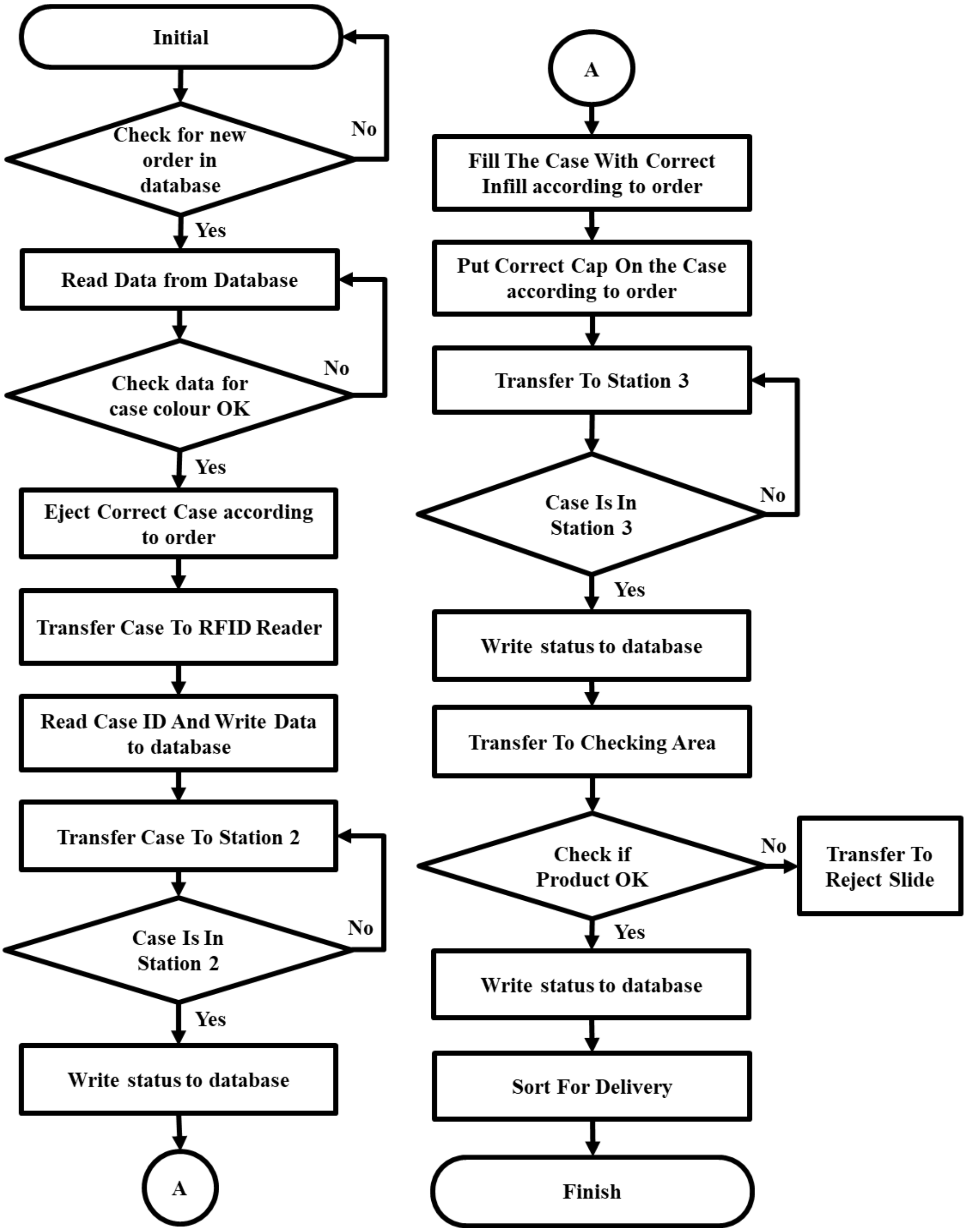

Figure 4.9: Overall operation flowchart

The SCADA software constantly checked the database for new entries. If there was a new entry, it would inform the controller to start the production process. It would read the database and determine the specification of the product it needed to produce. The production process would start for each station until it was finished and sorted. Throughout the production process, the progress of the assembly could be monitored. Factory personnel could check if there were any errors or problems during the whole production process. Furthermore, if there was a shortage of raw materials, the system will send an alert to refill the raw material.

4.3 Production Layout

After the intended product was determined, the next step was to build the product by first designing the production layout. As stated in Chapter Three, this prototype used an educational trainer from Festo. The original trainer was modified and upgraded to incorporate Industry 4.0 elements.

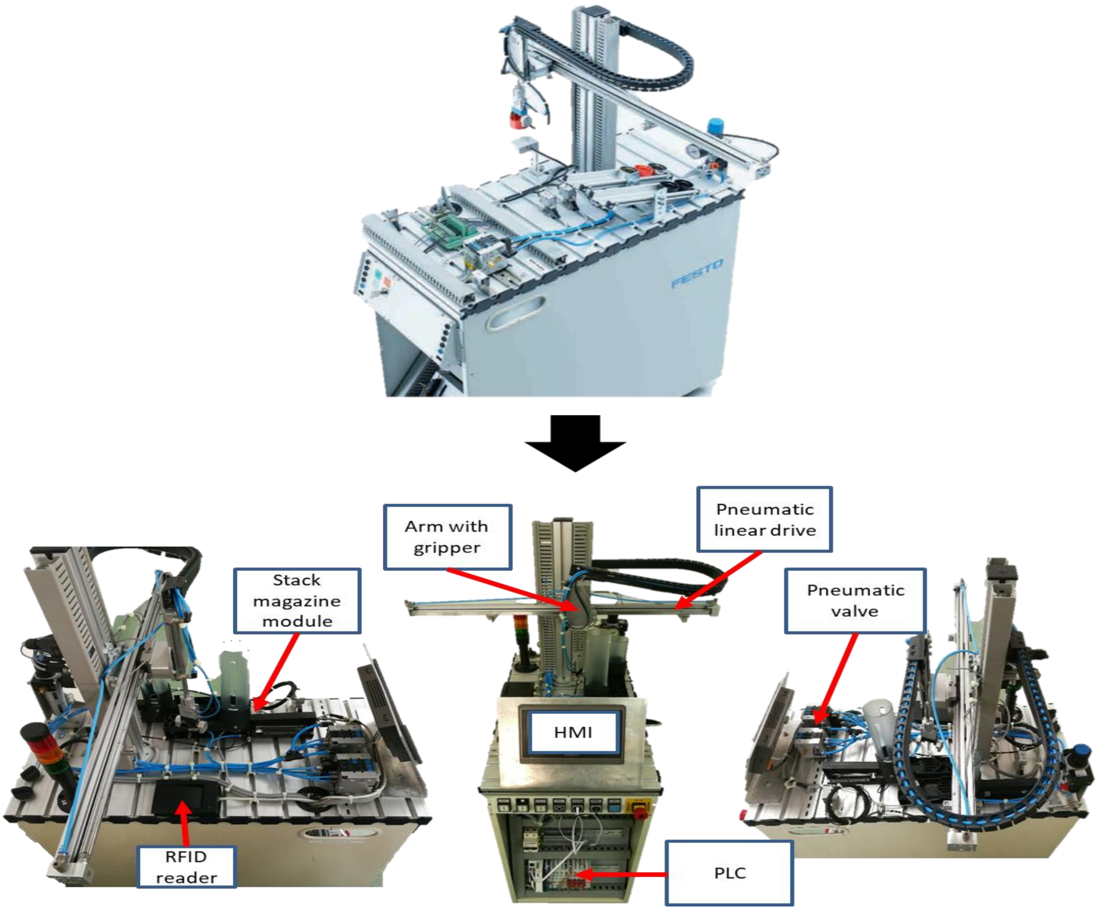

Figure 4.10: Comparison between the original station and the modified station

Figure 4.10 shows the original station in comparison to the modified station. The first production station was renamed the “Distributing Station”. This station was modified with additional components. Firstly, two stacks of magazine modules were added to the station. The two stack magazine modules are used to store the two different coloured cases respectively. A pneumatic linear drive equipped with a pneumatic gripper arm was used to pick the case and transfer it along the station. Another additional device that was added was an RFID reader that was used to read the RFID tags attached to the cases. The original station used physical pushbuttons as its control panel. This was upgraded into a touchscreen Human Machine Interface (HMI) display that acted as an interface to display the IO status and control certain IO functions. This was also to give a digitalized view of the physical signals or IO of the station.

Various digital sensors were used as inputs to the controller for monitoring and event triggering. Among others were the reed switch used to detect the piston in the pneumatic cylinder and various optical sensors to detect a workpiece. All of this needed to be wired correctly to the interface for it to work properly. As an addition to the original sensor, an analogue pressure sensor was added to continuously monitor the pneumatic pressure. This pressure sensor was connected to the analogue card of the PLC. The value was then displayed on the HMI and on the SCADA interface in real time. Thirteen digital inputs and eleven digital outputs were used in this station. Five pneumatics valves were also used to control the movements of the pneumatic components, mainly the pneumatic cylinders.

Another additional component was a digital power meter (DPM) used to obtain power parameters such as the voltage, ampere, power and frequency. This was to display the power parameter constantly in real time for monitoring purposes. The power meter transmits its data through an RS485 connection and using the Modbus protocol. To make the data exchange more efficient or to standardize the data type, a converter was used to convert the Modbus Remote Terminal Unit (RTU) or serial communication data to a Modbus Transmission Control Protocol (TCP) using the Ethernet. This way, it could connect directly to the LAN and data can be transmitted directly from the DPM to the SCADA software while still using the same Modbus protocol. On the interface of the SCADA software, this data can then be displayed in various ways such as a digital or analogue meter and can also be displayed in the form of a trending graph. The data can also be saved either on a hard drive of the server or in a database.

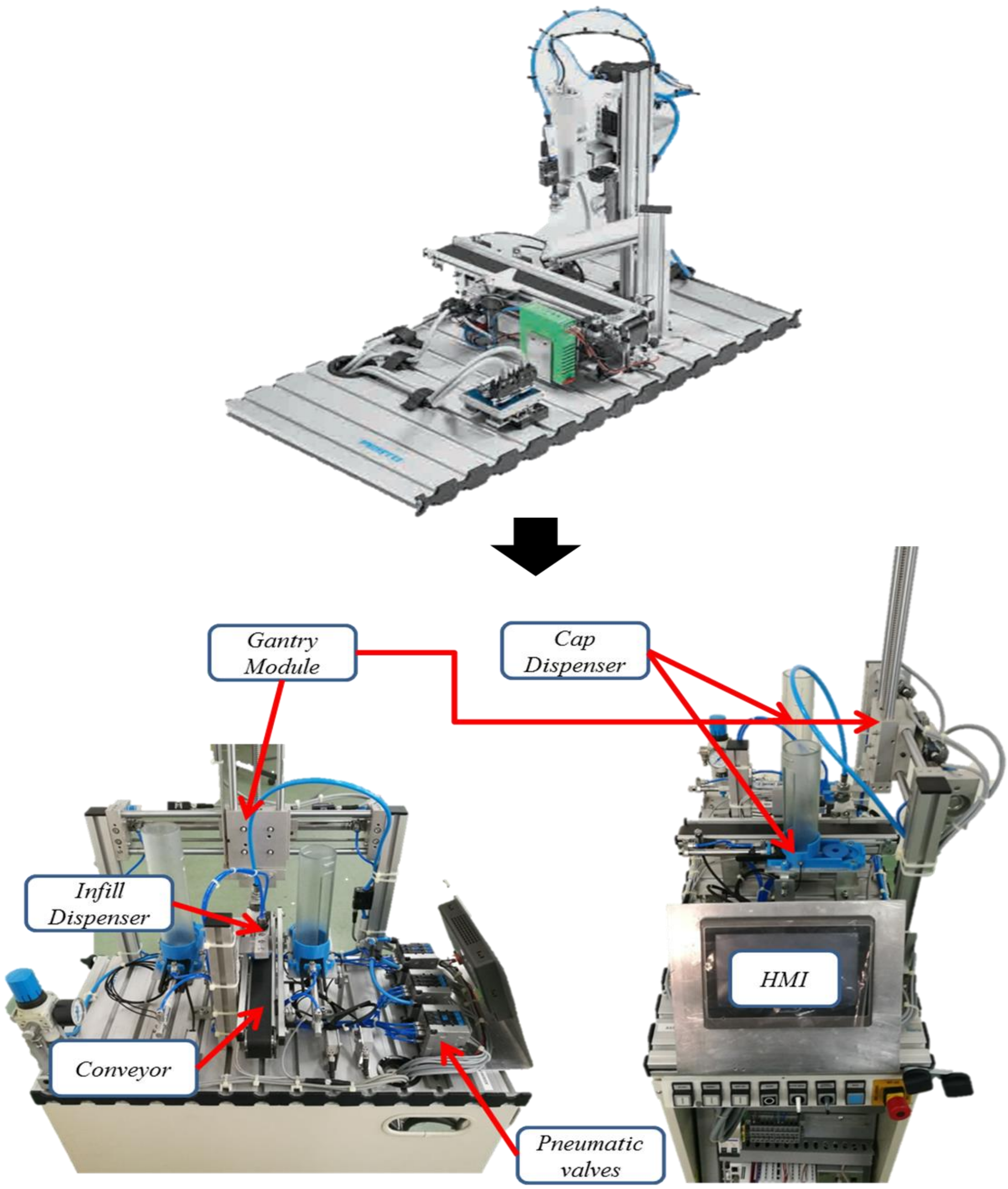

Figure 4.11: Comparison between the pick-and-place station and the modified station

The second production station was renamed as the "Processing Station". This station was not one of the standard MPS stations. Figure 4.11 shows the processing station and its main components. The original station was a pick-and-place station, but it was heavily modified and upgraded for this research. The upgrade of the original station into the new processing station was needed so that it could carry out the intended process of producing the intended product as already described. Among others, this station had the task to fill the cases with an infill, dispense the right cap colour and place it on the case. As this station was not a standard station, various components were put together to enable the production process. The conveyor system was used as it was and the vacuum suction system was also maintained from the previous station. The rest were either removed or modified. The product was transferred along the station to each process using a DC geared motor-powered conveyor belt which was from the original station. Thirteen inputs and fourteen outputs were connected to the PLC.

For the first process, a mechanism was needed to show the process of filing the case with something. Filling the case with liquid or granulates will cause a terrible mess each time. As this system was just a prototype, it was suggested that the infill was only represented by blowing air into the case. Two air nozzles were used for this purpose. Each nozzle represented a different kind of infill. Two single solenoid valves were used to control the airflow.

For the capping process, two cap dispenser modules were added to the station, one each for the two coloured caps. The cap dispenser module was used to separate the stacked caps. The original station did not have a cap dispenser. Thus, it needed to be taken from another station or fabricated. As there was no module available and to keep the cost low, it was decided that the module be fabricated. A cheap and fast option was to use the 3D printing method to fabricate the part. The 3D printer is also part of Industry 4.0 and in this case, it was used to fabricate the module swiftly and cheaply without minimum order. The module was designed using the CAD software and was then printed using a 3D printer. Another problem was the process of picking up the cap and assembling it in the case. To achieve this, the arm needed to stop at three locations accurately and this was hard to achieve when using a pneumatic cylinder as in the original pick-and-place station. Therefore, a two-axis, DC motor power gantry system was designed to pick the cap from two different locations and put it onto a case to complete the assembly. The vacuum suction system was used to hold the cap during the transfer process.

The third production station is called the “Sorting Station”. This station was a standard MPS station. This station checks and sorts the finished or rejected products. The products were sorted according to the delivery region or rejected into slides accordingly. The delivery region was set as East for slide one or West for slide two and the third slide was for the rejected products. The region data was extracted from the address of the customer stored in the database. This means that the PLC will retrieve data from the database through the SCADA software. In this station, eleven inputs and six outputs were used.

The product was transported along the station using a conveyor belt. Electro-pneumatic gates were used to sort out the end product into the slides accordingly. Optical sensors were used to check the colour of the product and to check whether the cap was on or not. Figure 4.12 shows the layout of the sorting station and its main components.

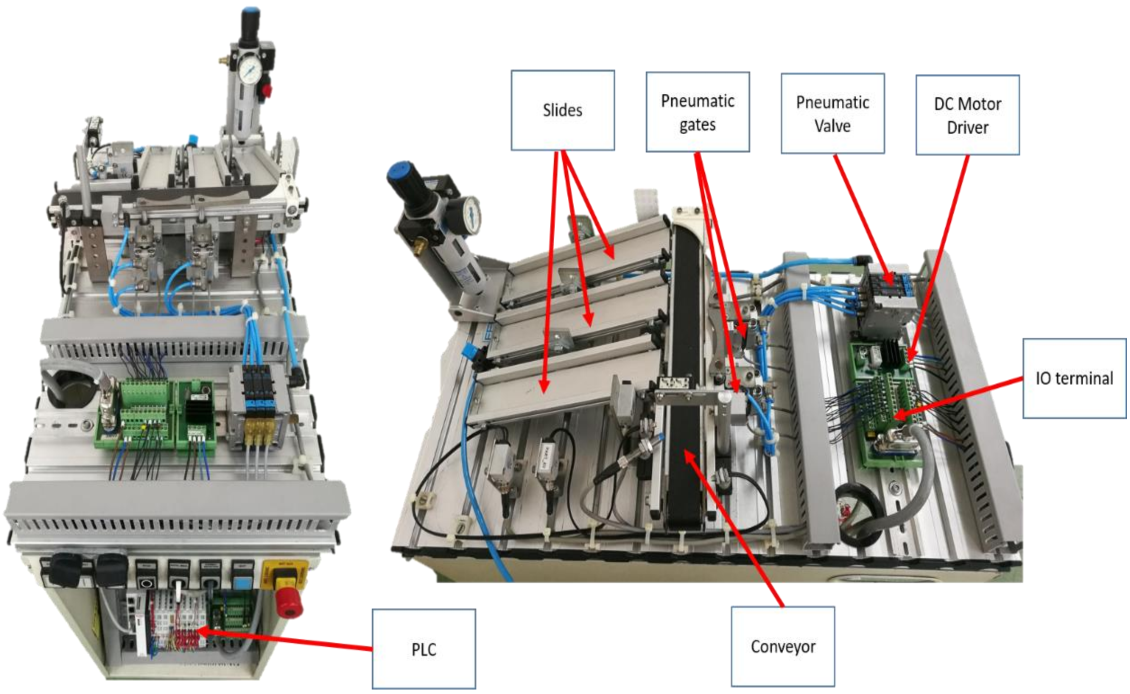

Figure 4.12: Layout of the Sorting station and its main components

Figure 4.13 shows the overall production layout of the system. It consists of the combination of the three stations, a server, and a router. The stations were arranged in a straight line to allow a direct and efficient flow of the material. Each station was controlled by its own PLC. The server hosted the database and SCADA software while the router acted as a gateway to the outside world through the Internet.

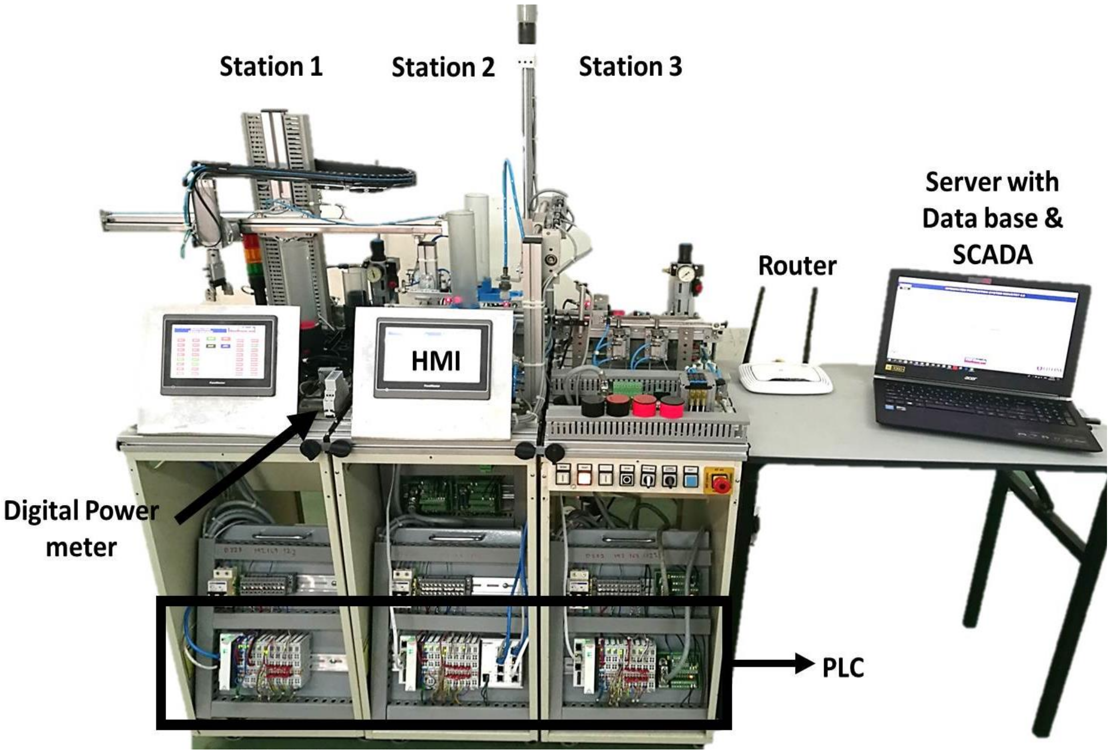

Figure 4.13: Overall Production Layout

Figure 4.14, shows the real view of each station in comparison to the graphical view in Figure 4.15. It also shows how it was connected and its major components including the sensors and actuators.

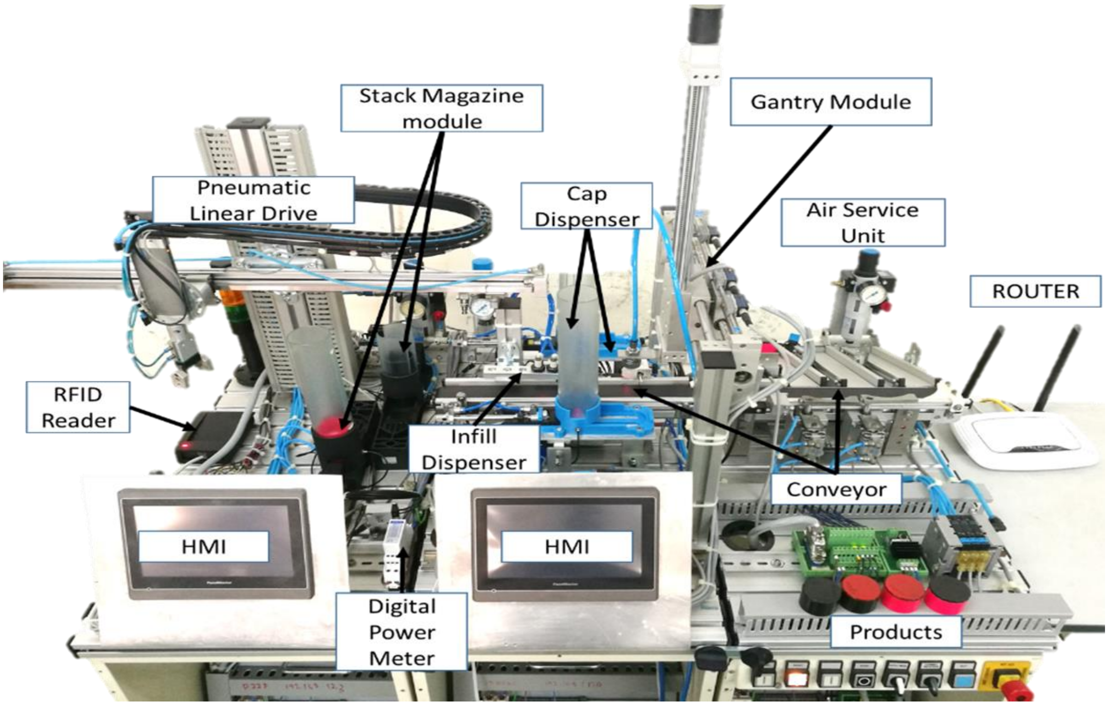

Figure 4.14: Real view of each station

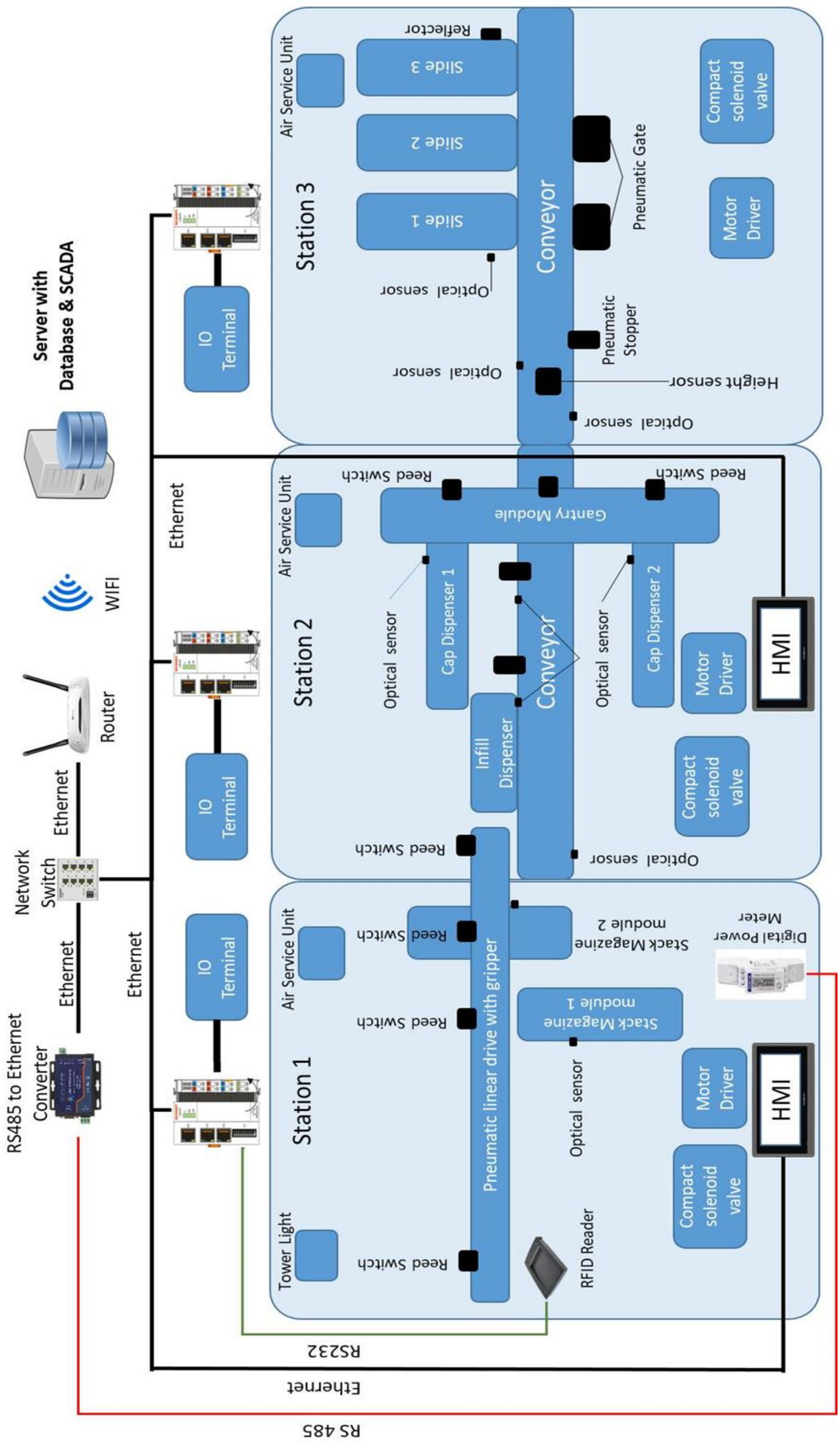

Figure 4.15: Graphical model overview of each station Real view of each station

4.4 The operation flow

4.4.1 The operation flow of Station 1

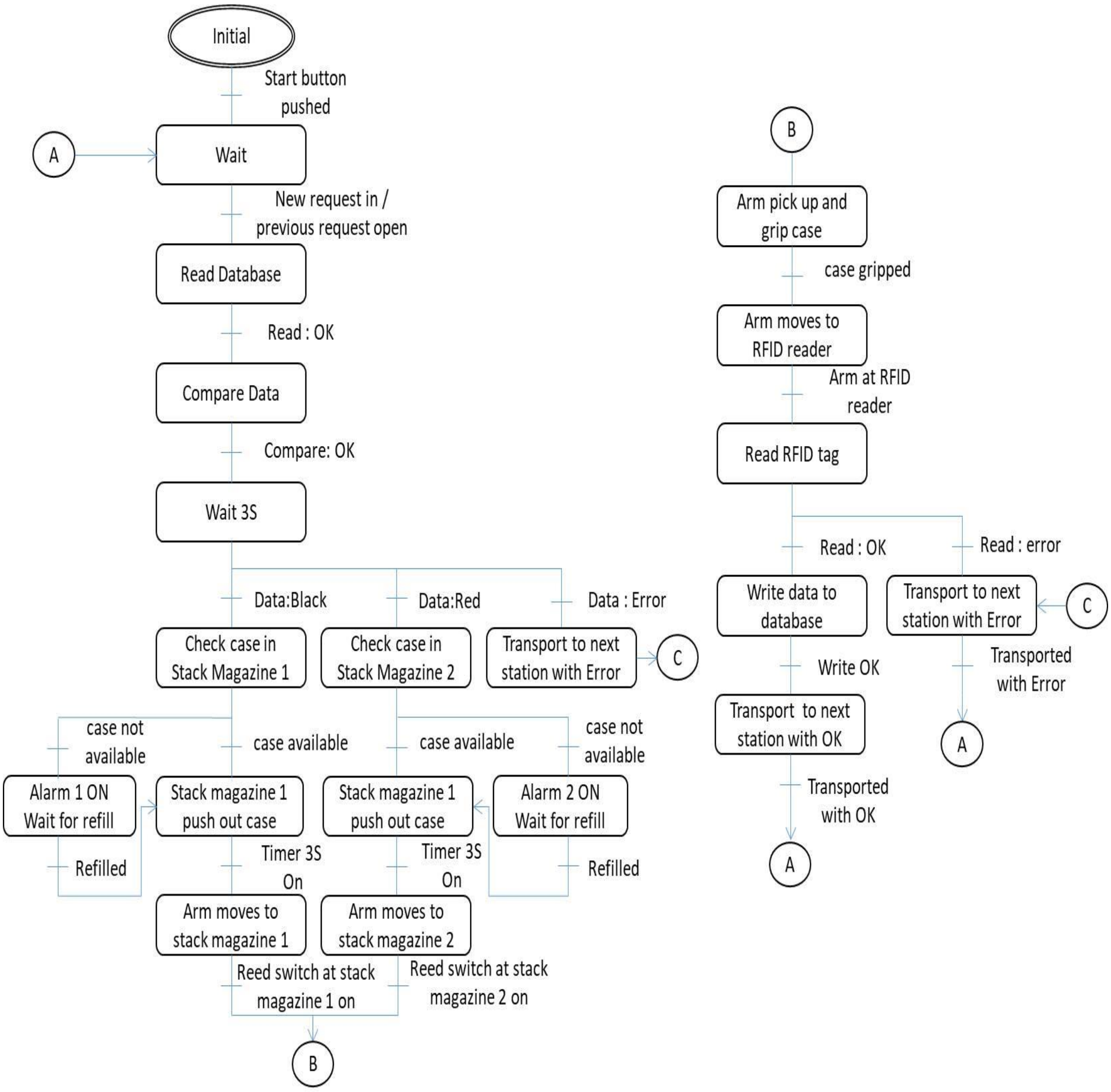

Figure 4.16: Operation flowchart of the distribution station

Figure 4.16 shows the operation flow of Station 1. The station must first be initialized, then the start button must be pressed for the station to be in standby mode. In the SCADA software, using the schedule function, the SCADA will activate a tag in the SCADA at an interval of every two seconds. This will invoke a script that was programmed to check a database for a new order. Thus, the database was configured. A table for various data was created in the database. Then the data was linked to tags in the SCADA software. This was done using the native function of the SCADA software or using SQL language in the script function. Before that, a connection between the tables in the database and SCADA was established. If there was a new order in the database, it would activate a tag linked to a variable in the PLC. Then, the PLC will request the order details from the database through the SCADA software. It will read the data on the database with the order information. It will check whether the customer had ordered a black case or a red case. Then, the stack magazine module will dispense the case accordingly. If there was no raw material in the stack magazine module, a sensor will detect this and send a signal linked to a tag in the SCADA software. This will trigger an alarm function set in the SCADA software. If not, the gripper will pick up the case accordingly and transport it to the RFID reader. The RFID reader will read the ID tag number in a single bit. This must then be added into a string and written in the database again through the SCADA software. This will assign an ID to the order. If the reader could not read the ID after five seconds, the case is transported to the next station directly. If not, the number of the ID tag is displayed on the HMI. Then the case is transferred to the next station. The first station will send a confirmation code to the second station. As the production is running, users can request a certain status from the system. A customer, for example, can request the status of their order. This request is transferred to the server through the Internet. As long as the product has not been assembled or the system has not read the data from the database, a customer can still make changes to their order. This enables last minute changes. Part of the PLC program for station one is shown in appendix D.

4.4.2 The operation flow of Station 2

Figure 4.17 shows the operation flow of the processing station. The function of the processing station was to fill the case with either infill and put a cap on the case. This station waits for a confirmation code and for the case from the first station. If it received a reject confirmation code, the case would be transferred directly to the next station. If not, the system reads the order details from the database and the case is transferred to the filling area. The case is filled with either one infill according to the order. Then it dispenses the cap according to the colour specified in the order details. Before that, it will check if there is a cap available in the cap dispensing module. If not, like before, it will trigger a variable that will set off an alarm in the SCADA software. If not, the gantry module will pick up the cap and place it on the case. After that, it is transferred to the next station together with a confirmation code. Part of the PLC program for station two is shown in Appendix E.

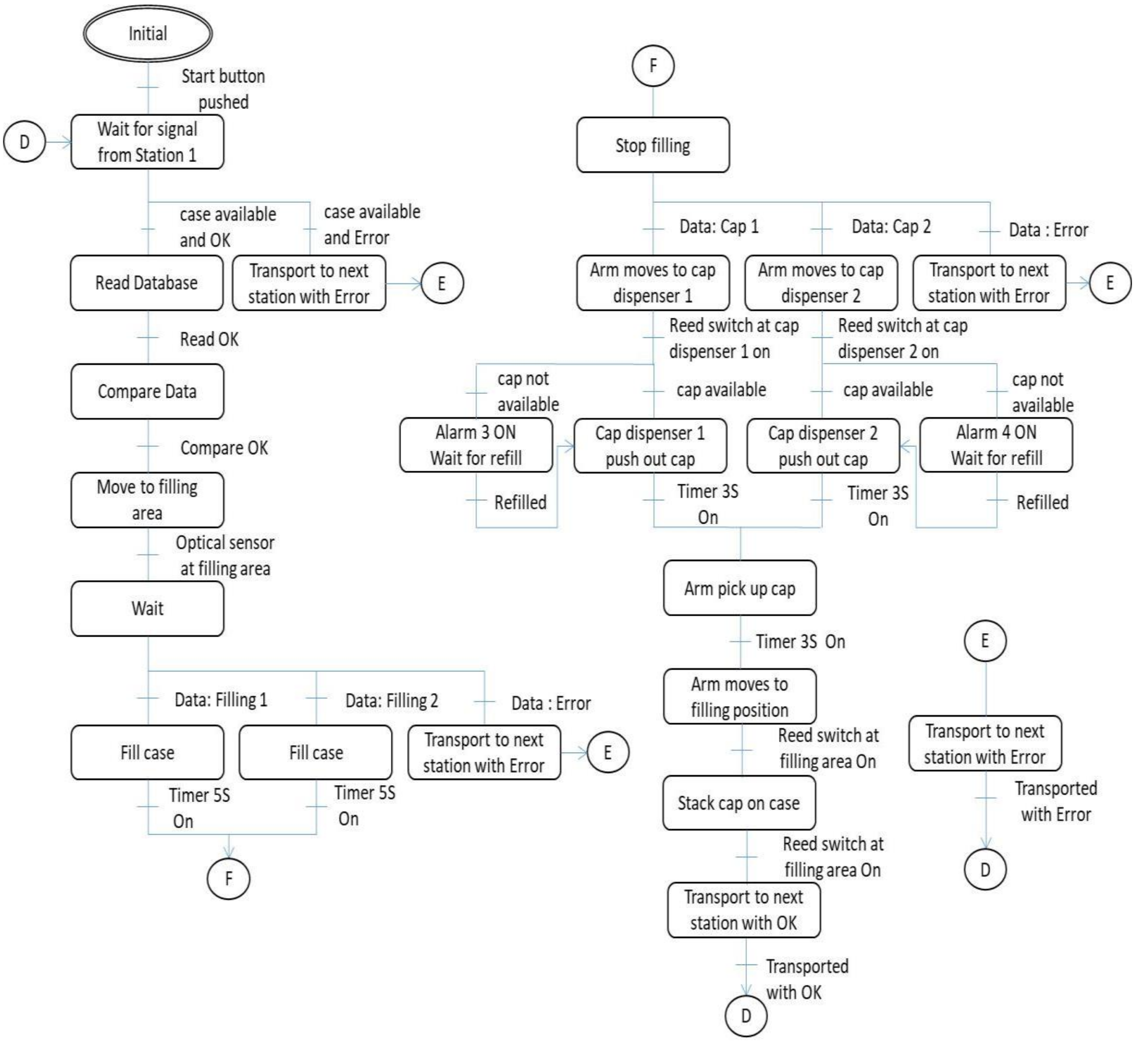

Figure 4.17: Operation flowchart of the processing station

4.4.3 The operation flow of Station 3

Figure 4.18 shows the operation flow of the sorting station. This station inspects the assembled product and sorts it. Again, this station waits for the confirmation code and the assembled product from the previous station. If it receives a reject confirmation code, it rejects the third slide. If not, the product is transferred to the checking point. The controller again read the data from the database. This was to confirm the specification of the product and check the delivery region. At the checking point, sensors were used to check the colour of the case and whether a cap was on the case or not. The data from the sensors were cross-referenced with the data from the database and was checked. If everything was fine, it was sorted according to the region on either slide one or slide two and if not, it was transported to the third slide. With this, the manufacturing of the product was completed and the cycle will start over. Part of the PLC program for station three is shown in appendix F.

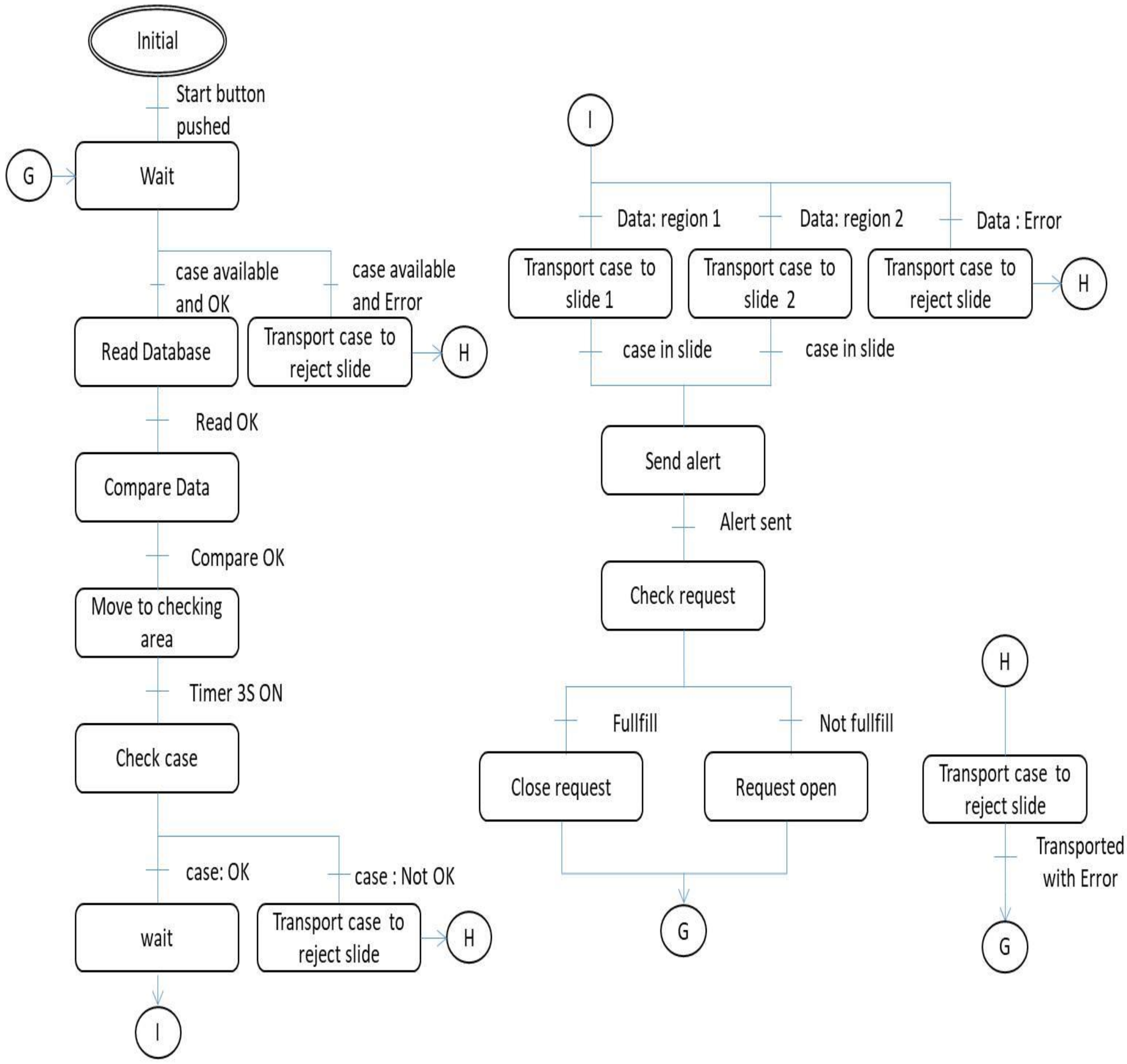

Figure 4.18: Operation flowchart of the sorting station

4.5 Network Setup

Figure 4.19 shows the overall network setup and how the devices in this prototype are connected. First are the controllers that were interconnected with one another using an Ethernet connection using the ADS protocol. Each of the controllers was assigned a fixed IP address that was set on the controller itself. The controller was also connected to the HMI using the same method and protocol. The server was also given a fixed IP which was set on the server itself. For the digital power meter, the IP address was set on the router by fixing it to the MAC address of the device. This was as suggested in [47] to avoid miscommunication as the IP address needed to be pre-programmed in the devices. These controllers were connected to a fast network switch in a local area network (LAN). On the LAN, there was a router that managed the LAN. This router was connected to the Internet and acted as a gateway between the Internet and the devices in the LAN.

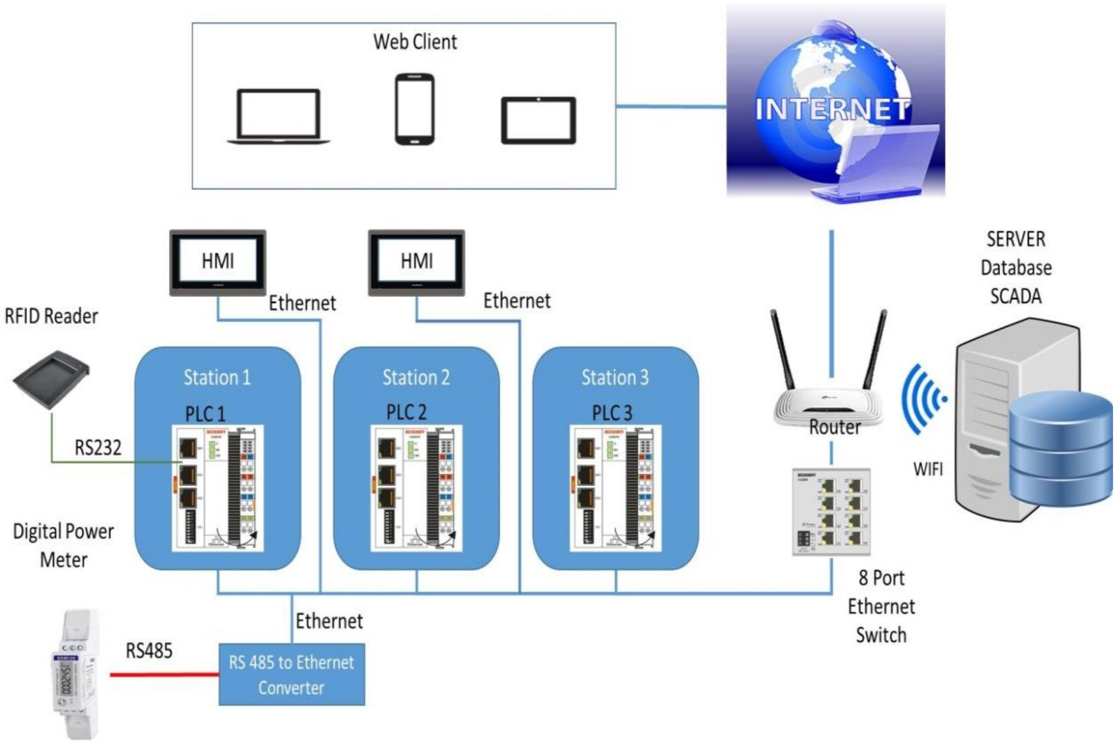

Figure 4.19: Overall network setup

Other connections included a serial RS232 connection for the RFID reader. This reader was connected directly to the controller. This means access to data from the reader was only possible through the controller. Other than that, there was also a digital power meter (DPM) which was connected using a serial RS485 connection with Modbus protocol. In contrast to RS232, RS485 can communicate with many devices. To open the access to the DPM, an RS485 to Ethernet converter was used to convert the signal so that the DPM could be directly connected to the LAN.

Lastly was the server which hosted the SCADA software and the database. The server was connected to the router through Wi-Fi. This gave access to the devices on the same LAN and to the Internet. The server service was configured using Microsoft IIS as stated before. On this server, the SCADA software which was the backbone of the system was installed and configured. The SCADA software can communicate with the controllers through the LAN network using ADS protocol. It could also receive information from the DPM using the Modbus TCP protocol. The database could communicate internally with the SCADA software on the server. Remote access from web clients was also done using the SCADA software as it had this function. This saved development time as the same interface can be used locally or for remote access.

4.6 Interface Layout

The user interface is a graphical user interface. This makes it is easy to reconfigure or be modified in the future compared to a physical user interface which is complicated and requires a lot of wiring. This is important for an Industry 4.0 system as it must adapt to changes quickly. A graphical user interface allows the owner to add or remove any page, function, button or any interface necessary without hassle.

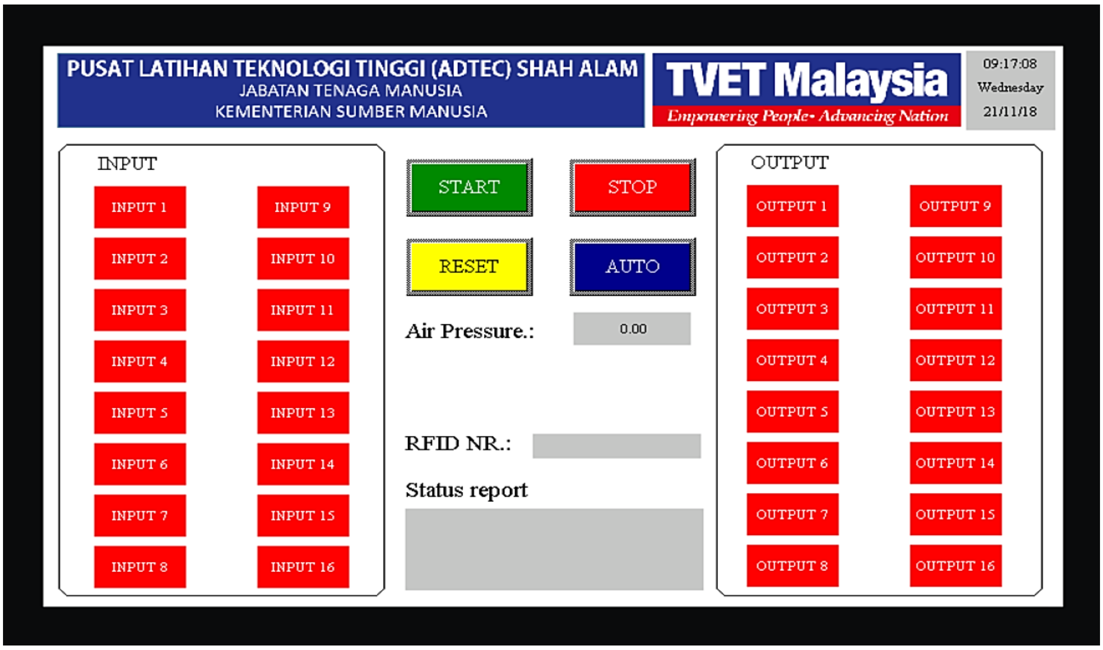

Figure 4.20: HMI display layout

There were two main interfaces for this system. The first interface was the HMI touchscreen panel that was mounted directly at station one and two. This interface was mainly to monitor the inputs and outputs of each station locally. It was also used to reset, stop or start the machine according to the pre-programmed operation. Figure 4.20 shows the HMI layout of the interface on station one. The layout was created using the software. Each of the functions or items in the layout such as the buttons and lamps needed to be linked to the PLC variable. This required a driver to access the variable on the PLC. The connection between the PLC and the HMI needed to be configured beforehand. Among others, the IP address and port.

The main interface was created using the SCADA software and is displayed on a computer screen of the server. This interface linked variables in the PLC, data in the database and tags in the SCADA software. The variable from the PLC was linked to the tags in SCADA or was linked directly to components in the SCADA interface such as a button. Before starting, the connection between the PLC and the SCADA software needed to be established by setting the IP and port. Then, the variable from the PLC can be imported directly into the PLC and be assigned to a tag or components.

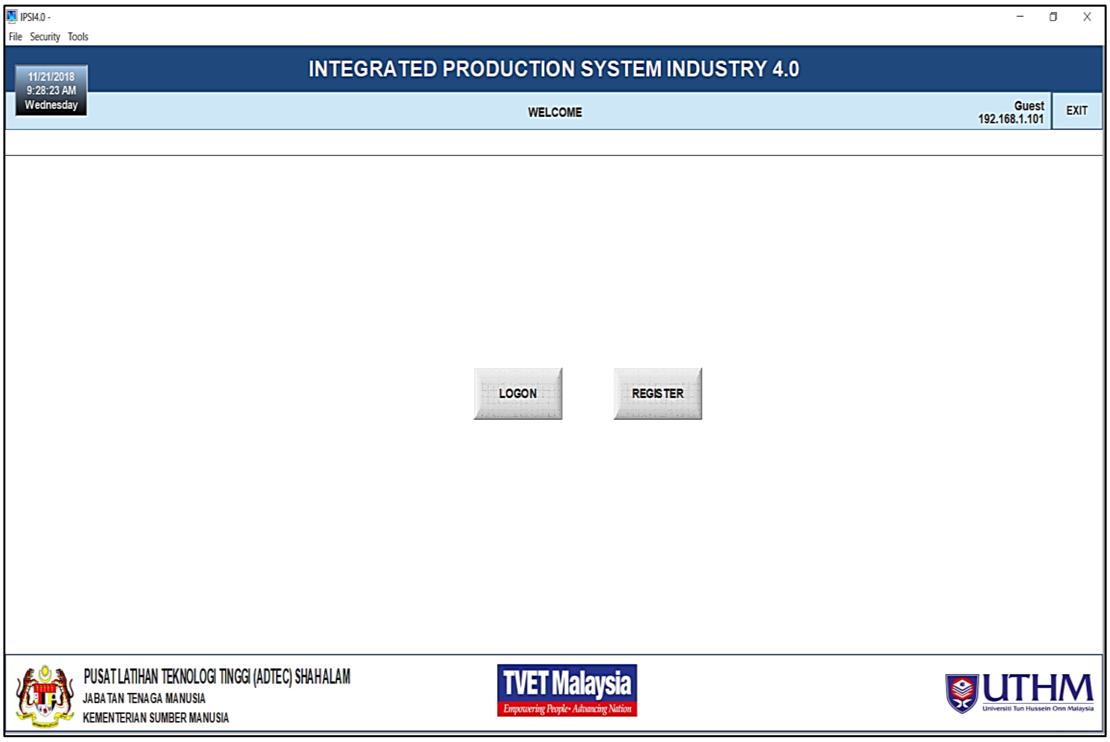

Figure 4.21: Login page of the interface system

The SCADA system allows multi-role user access. The users are sorted into workgroups, for example, consumers, engineers and admin. Each workgroup is given a certain level of access. Each level could access certain functions or pages on the interface. Users need to log in their credentials and according to the workgroup that they have been assigned to and may access certain functions. Figure 4.21 shows the login page. This is for security purposes, by dividing the access for each user group whilst still using the same software to develop it.

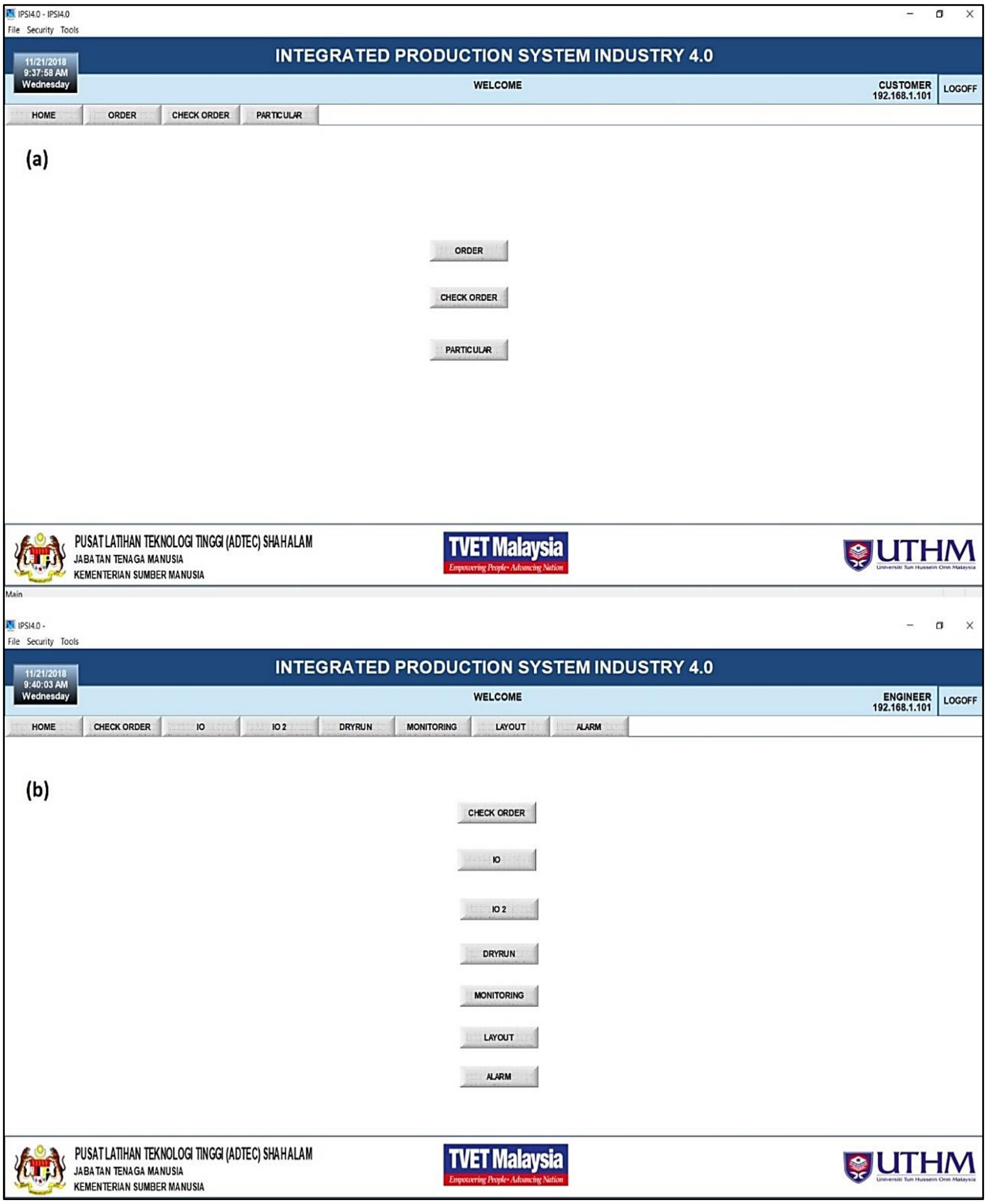

Figure 4.22: (a) Customer main page, (b) engineer main page

Figure 4.22 shows the different pages a user can see when they log in. Figure 4.22 (a) shows the customer's main page which has fewer functions than the one shown in Figure 4.22 (b) which is for an engineer. The customer can only make an order in comparison to the engineer who has access to the system itself, for example, the IO.

One of the most important pages is the ordering page. In this page, a user can make an order. Figure 4.23 shows the ordering page of the system. In this page, a user can choose or customize the product they want to order. It also displays the user data such as delivery contact and address which has already been saved in the database. The user can edit the delivery address and billing address and this will be saved in the database. The orders are organized in the database in a table according to order ID which is generated each time an order is made. This is checked by the SCADA software to see if there is a new order or not. The users can also check their particulars or the status of their order by pressing the Particular and Check Order buttons. During this process, there is a lot of data exchange between the PLC, SCADA and the database. Therefore, each component needs to be programmed and linked with each other carefully and precisely to avoid mess up, especially in the orders.

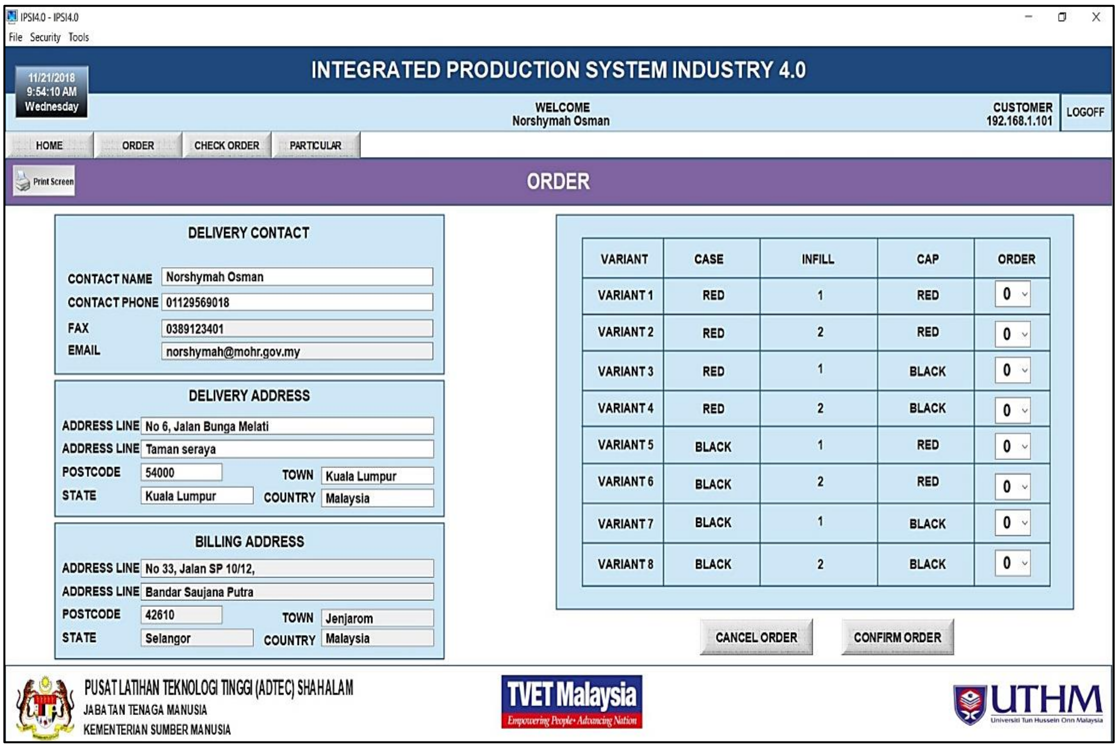

Figure 4.23: Ordering page

Other pages are specifically for the use of factory personnel such as engineers or maintenance personnel. These pages mainly show the status of the machines, its parameter and trending graphs or to operate the system manually. These functions can also be accessed remotely. Figure 4.24 shows the status of all the IO connected to the system, whether it is on or off. The variable from the PLC, mainly the inputs and outputs, are linked to the components in the interface directly. This means that when the state of these IOs change, the changes are reflected or can be seen in the interface.

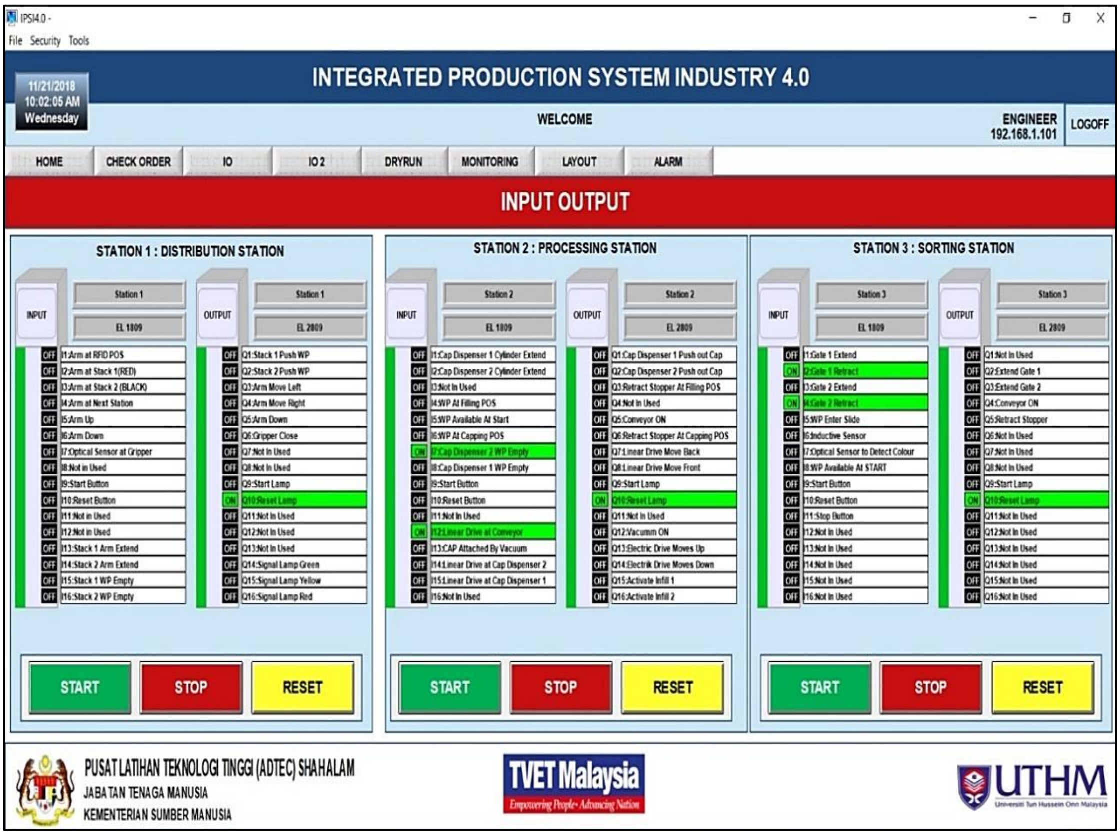

Figure 4.24: The IO status page

Figure 4.25 shows the power monitoring page. In this page, certain parameters concerning the power system such as the voltage, ampere, power factor, energy, and frequency are monitored and displayed continuously at near to real time. The purpose of this page is to show the ability to display and record various parameter that can be monitored continuously. The monitoring of these parameters ensures that the system is always operating within its allowable parameter. It can also be used to monitor the amount of energy used for energy monitoring purposes. The data are displayed in the form of analogue meters and trending graphs. The data collected can be saved on the server or linked to the database. These data are collected from the attached DPM. In the SCADA software, the Modbus TCP driver was added so that it could read the data from the DPM. The data from the DPM are coded using the Modbus protocol. It consists of several function codes that can be used to call the parameter needed. For example, the voltage data uses the function code 04 with the function of reading input registers and it is located at the address 30001. This is one of the advantages of using SCADA in which it could connect to various devices with different protocols simultaneously.

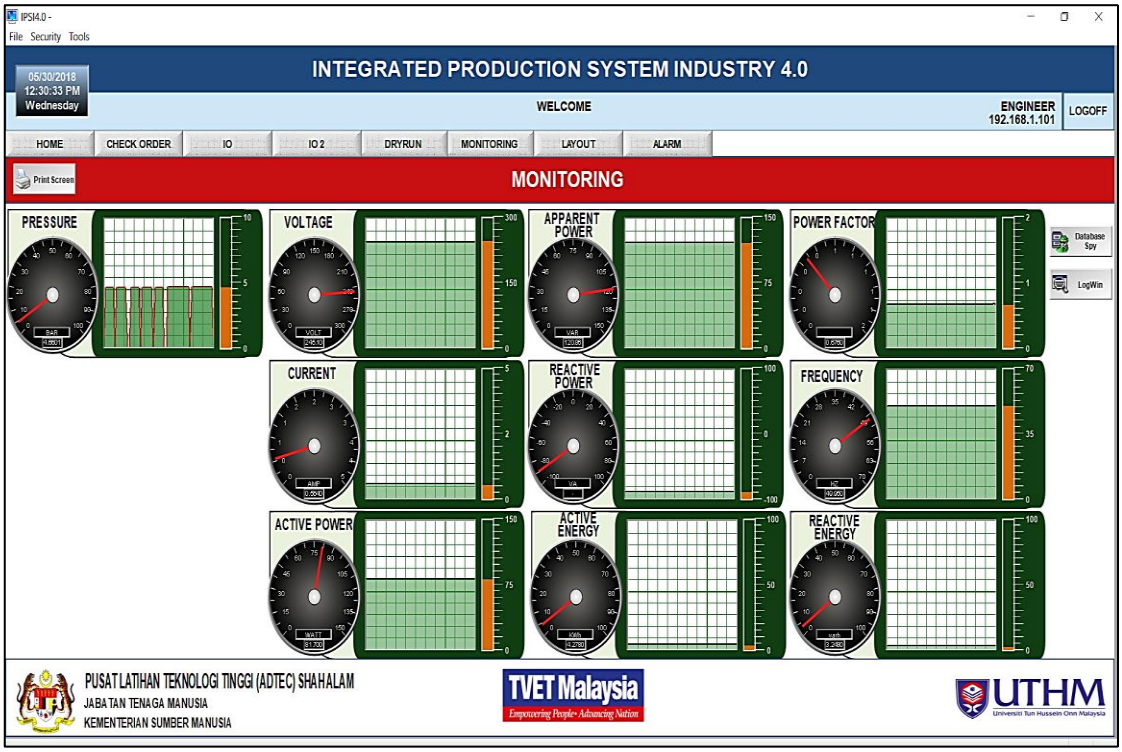

Figure 4.25: The power monitoring page

Figure 4.26 shows the dry run page or the manual operation page. In this page, the user can operate certain functions of the system manually. Users can turn on certain outputs or functions or even configure and produce any variant of the product. This page is mainly for testing, maintenance and troubleshooting purposes. The components in this page are linked to the variables in the PLC so that various functions of the station can be controlled individually.

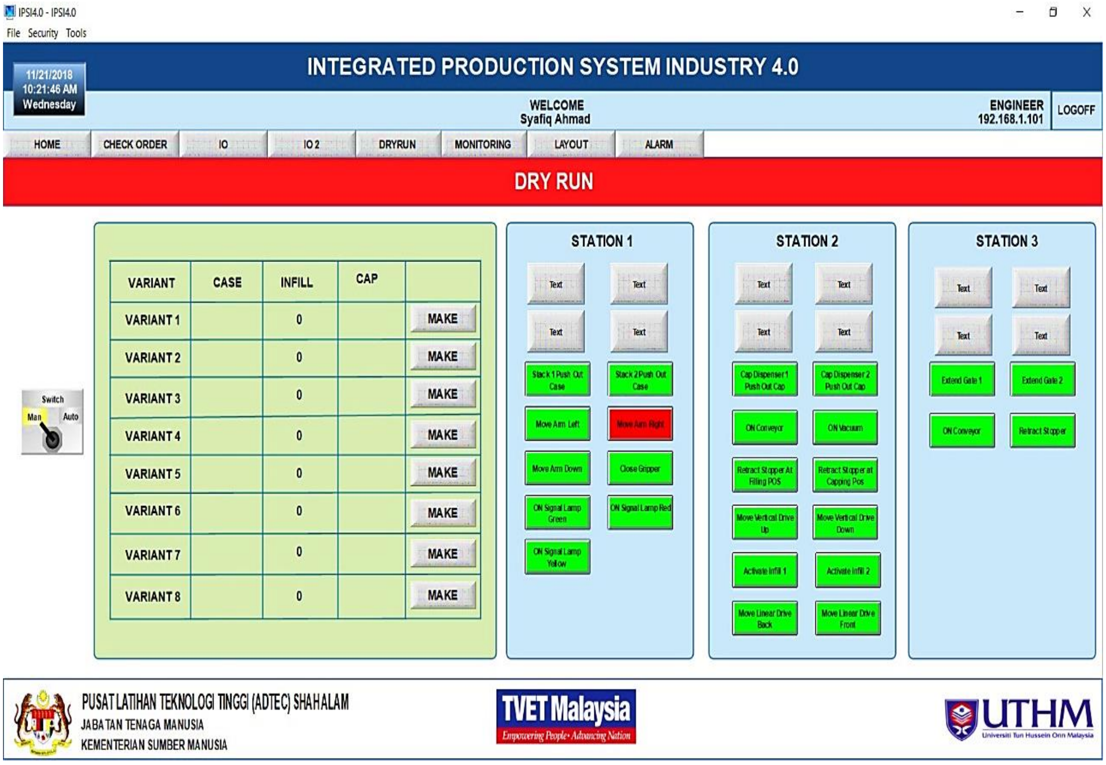

Figure 4.26: The dry run page of the system.

Another important page is the alarm page. This page shows if there is an alarm triggered by the system. For example, if the raw material has run out, or if any parameter monitored is out of its limit for example if the air pressure is too low or too high. The limit is set according to each devices specification sheet provided by the manufacturer. Failure to maintain the limit of these parameters may cause damage to the devices or they might not operate properly. With this system, various parameters are constantly and automatically monitored. Figure 4.27 shows the alarm page of this system. In this page, the user can set the limit of the parameter monitored. The alarm function was set up in SCADA. It was assigned to monitor certain variables in the PLCs. The message that appears in the alarm terminal is pre-programmed. In the terminal, the time and date of when the alarm is triggered are recorded.

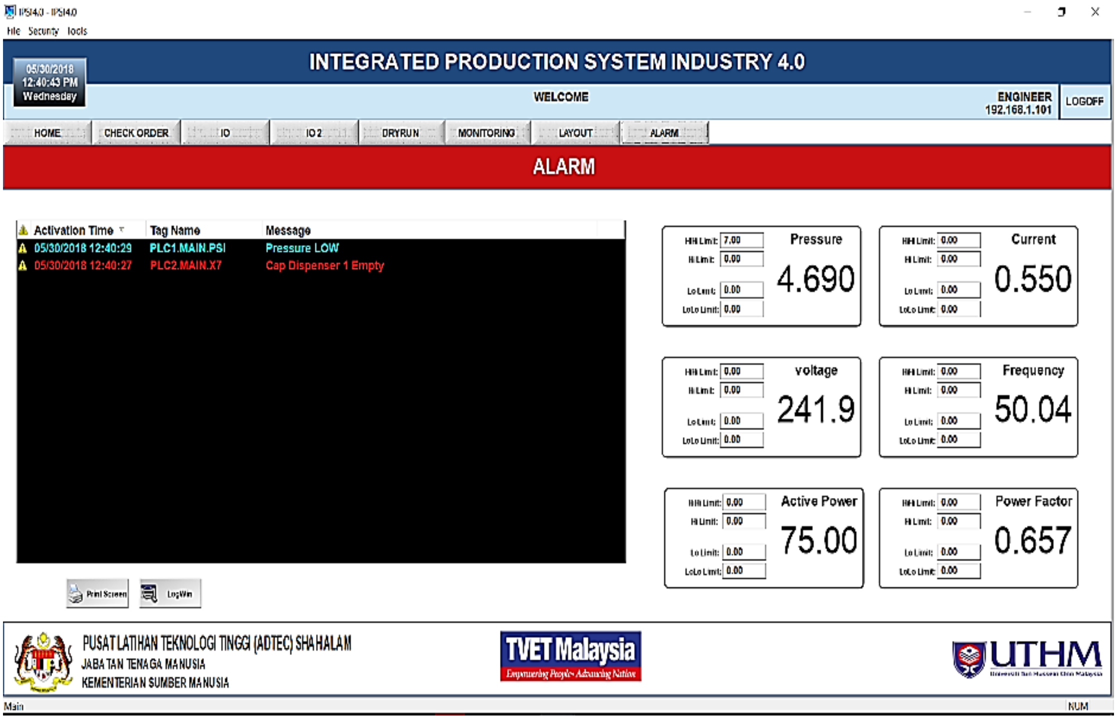

Figure 4.27: The alarm page of the system

CHAPTER 5

EVALUATION OF RESULTS AND DISCUSSION

This chapter discusses the result of the evaluation carried out on the prototype. The first evaluation was the system functional test of the whole system, followed by the evaluation of the system using the VDMA Industry 4.0 toolbox. This was to see the potential level of the Industry 4.0 system and was divided into several application levels. It was then compared with a normal education trainer.

5.1 Functionality Test Result

The functionality test was carried out to see whether the system could function according to the desired operation. This was to ensure the functionality of the overall system and sub-systems and that they were integrated with one another correctly. It was also to confirm the ability of the devices to exchange data. Testing the correct functionality of the whole system and whether it met the requirements listed before the development started. This also to prove that a prototype could be built and that a system can be integrated with each other using currently available parts. A functional system is important to ensure that the evaluation that is later carried out will give an undisputed result. Each test was carried out at least five times to ensure its reliability.

The first test that was carried out was to test the IO connection of each component. A checklist was created to systematically check all of these IOs as can be seen in Appendix A, B and C. From the test that was conducted, all the IOs were working and were wired according to the IO allocation list. During the initial tests, there were some IOs that were not wired correctly. This was rectified before the next test was carried out. The next test was to check the movements and functions of the various actuators on the system manually using the user interface. It was also to configure the movement of the mechanical parts, for example, its speed and to configure sensors' location relative to the movement part or workpiece. For example, to adjust the location of the sensor used to detect when a cylinder is extended. From the conducted test, the functionality of each system was tested and validated. Other than the IO, the digitalization of various parameter of the system was also checked and confirmed using various measuring tools. Among others, the air pressure was checked using a pressure gauge, the voltage was checked using a multi-meter and the current was checked using a clamp meter. Data that is displayed on the devices is also compared to the data which is displayed on the user interface. Table 5.1 shows the results of these tests. As can be seen, there are some differences. Also, the data displayed is more accurate.

Table 5.1: Test result comparison

Item	**Parameter**	**Average Reading displayed on the device**	**Average Reading displayed on the screen**	**Average Reading from measuring tools**
1	Air Pressure	Not available	5.064 Bar	5 Bar
2	Voltage	242.2 Volt	242.2 Volt	244.2 Volt
3	Current	0.54 A	0.549 A	0.53 A

Next was the testing of the PLC program. Step-By-Step execution of the program sequence was carried out. During this time, a lot of debugging and reprogramming was done to ensure that the system ran as it was supposed to. In the end, the system was able to operate as intended and the system managed to produce the intended product according to the correct specification. After that, the connection between the system and the SCADA software was tested. In the SCADA software, the output monitor panel was checked for connection error. The link between the physical IOs or data from various devices such as the PLC and the tag in the SCADA software were checked and confirmed. Each of the linked data was confirmed to be able to exchange data correctly and consistently. The data displayed in the interface of the SCADA system was confirmed to be functioning as intended. There is a function in the SCADA software that can be used called the Database Spy to check the data that is received by the SCADA software. The link between the system and the database was also confirmed. This was done by checking whether particulars that are keyed in the particular page of the user interface were correctly inserted in the database. Figure 5.1 shows the data that were keyed in the particular page and figure 5.2 shows the data that were inserted in the database. As can be seen, the particulars that were keyed in the particular page are the same as the particulars inserted in the database that was checked using the Microsoft SQL Server Management studio.

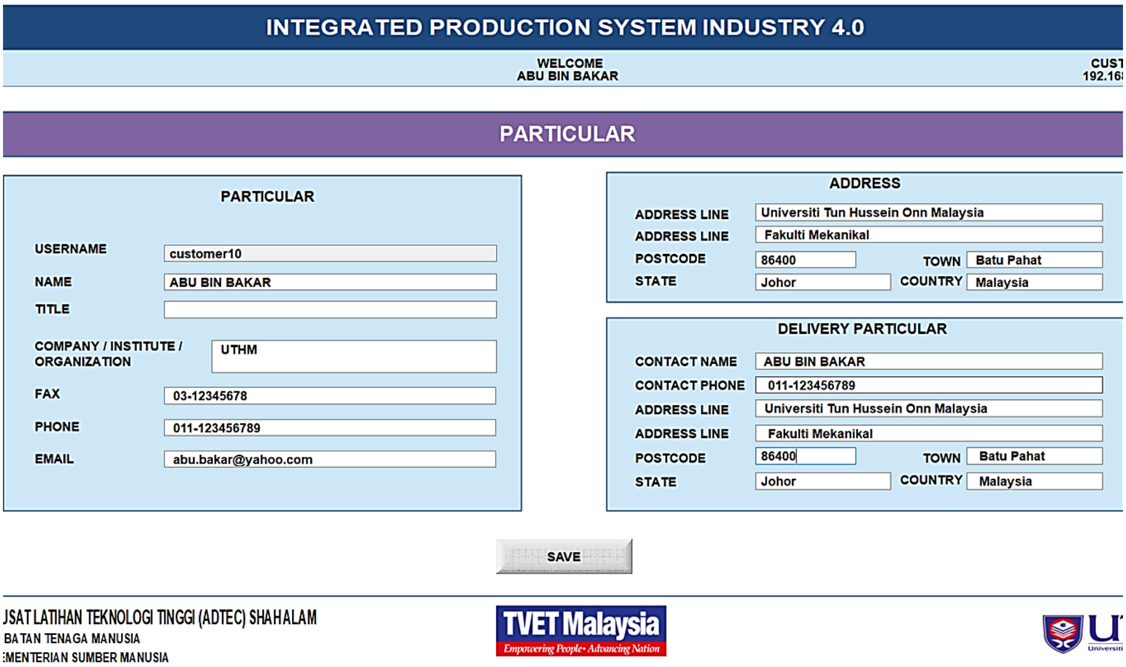

Figure 5.1: Data keyed in the user interface

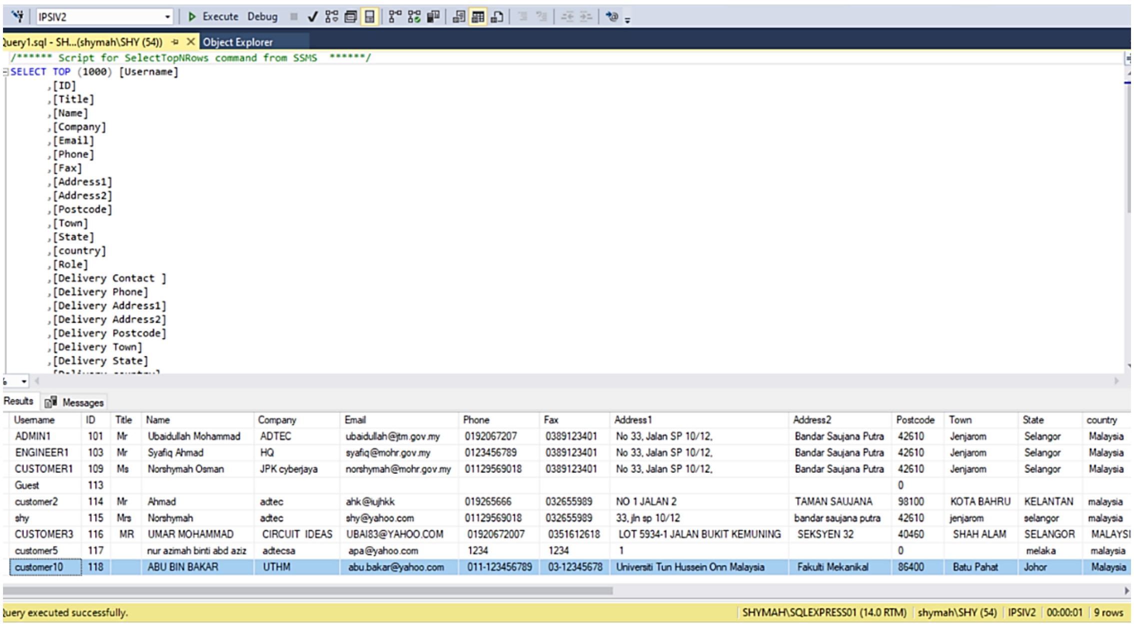

Figure 5.2: Data inserted into the database

After that, a pilot test was carried out. During this test, the system was turned on and various product variants were manufactured randomly to see the reliability of the system. The results were that the system was able to produce all eight variants randomly without any reprogramming of the system. The cycle time to produce each variant individually and to produce all eight variant in one order was also taken. Table 5.2 shows the cycle time taken to produce each variant of the product individually. Table 5.3 shows the cycle time taken to produce all eight variant of the product in one order.

Table 5.2: Cycle time for each variant.

Item	**Variant**	**Average Cycle time**
1	Variant 1	1 Minute and 19 Seconds
2	Variant 2	1 Minute and 18 Seconds
3	Variant 3	1 Minute and 8 Seconds
4	Variant 4	1 Minute and 6 Seconds
5	Variant 5	1 Minute and 19 Seconds
6	Variant 6	1 Minute and 21 Seconds
7	Variant 7	1 Minute and 8 Seconds
8	Variant 8	1 Minute and 9 Seconds
Total time to produce 8 variant individually		**9 Minute and 48 Seconds**

Table 5.3: Cycle time to produce eight variant in one order

Item	**Average Cycle time to produce all eight variant in one order**	**Average Cycle time to produce eight variant individually**
1	7 Minute and 27 Seconds	9 Minute and 48 Seconds

The alarm function of the system was also checked. Among others is to check the alarm function when the system has run out of raw material. Other than that, the parameter limit of parameters that can be tested such as the air pressure. The test result shows that an alarm is triggered when the parameter is out of limit. The alarm description is shown on the alarm page and a beeping sound will come out. Another test that was carried out is to test the reading of the RFID tag number by the RFID reader that is displayed on the PLC. As explained, the RFID tag does not have the ID number imprinted on the tag. Therefore, each RFID tag was read three times to check for consistency. Table 5.4 shows the reading of the RFID tag number for eight tags. As can be seen, for each RFID tag, the reading is the same.

Table 5.4: RFID tag number that was read by the RFID reader

Item	**RFID Tag Number Reading 1**	**RFID Tag Number Reading 2**	**RFID Tag Number Reading 3**
1	0008659743	0008659743	0008659743
2	0008264958	0008264958	0008264958
3	0008560912	0008560912	0008560912
4	0008949714	0008949714	0008949714
5	0008663116	0008663116	0008663116
6	0003943582	0003943582	0003943582
7	0003938693	0003938693	0003938693
8	003988111	003988111	003988111

Lastly was the remote access test. This test was carried out to test the remote access of the system. During the test, it was found that there were a few limitations due to software capability. For example, the application can only be opened using the Internet Explorer software, and certain modifications to the security level on the browser must be adjusted. Overall, the system responded well when operating remotely. It was able to carry out its functions the same as the local interface.

5.2 Requirement Cross-check

After the prototype function have been confirmed, the proposed requirement of the system is cross check with the actual system to see whether it has been fulfilled or not and how it was done. Table 5.5 shows the proposed requirement of the system and how it was fulfilled.

Table 5.5: List of Requirement that needs to be fulfilled by the prototype

Item	Proposed Requirement	Actual Prototype
1	The prototype must show the concept of mass customization.	The prototype uses a modular product concept in which customer could mix and max their preferences to create a specific product. Although it is not a fully customized product, the system managed to produce eight variant of the product without any reprogramming of the system.
2	Prototype implement a decentralize control concept.	The prototype uses a decentralized control in which each of the stations was assigned its own PLC and there is no centralized controller.
3	Digitalization of the system	Signals of the IO are digitalized and displayed on a screen. IOs are connected to the PLCs or connected to the network and captured by the SCADA software.
4	The system must be interconnected to exchange data with each other using industrial Ethernet or field bus connection	Various devices including the PLC, Server and digital power meter is interconnected with each other mainly using Ethernet connection to create a LAN. The PLCs are communicating with each other using Industrial Ethernet technology. The digital power meter is connected using RS485 connecting and Modbus protocol. The RFID is connected to the PLC using RS 232 connection.

5	The system uses a single interface to manage the data exchange between various systems.	Various system or devices are interconnected with each other through the SCADA software that delegates the exchange of data between. This also includes the connection to a database.
6	The system consists of a digitalized user interface that can be used for local access or remote access to show the IO statuses of the system.	There are two users interface developed for the system. The first one is a local interface which is directly at the station. This is done by replacing the physical control panel with digitalized touch screen HMIs. The second user interface is using the SCADA software itself for local and remote access through the Internet. The second interface implements a multi-role user concept in which different personal have access to different interface depending on their clearance level.
7	The system must integrate ICT tools such as a database.	The system is connected to a database also using the SCADA software. This is mainly to regulate and store data concerning order made by a customer including their particular. It is also used to store a certain parameter of the system and to generate a report.
8	Integration of an identification system to identify each product.	The system uses RFID technology for identification purposes to track each product. Each product is attached to an RFID tag. The RFID reader is connected to a PLC.

5.3 VDMA Industry 4.0 Toolbox Evaluation Result

The next evaluation was conducted using the VDMA Industry 4.0 toolbox. As explained before, this toolbox was used to determine the Industry 4.0 application level of a system. There were six aspects that were evaluated. The evaluation was carried out individually by comparing the criteria of each level with the prototype to determine the level it had achieved and the evaluation was carried out before and after the conversion.

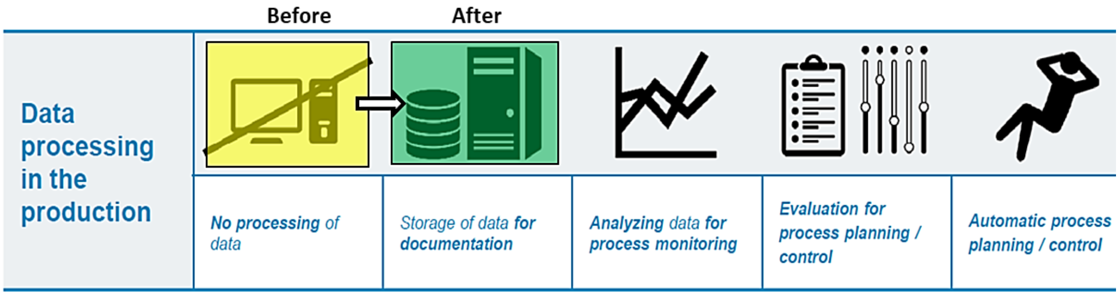

Figure 5.3: Criteria of each level for the first aspect of VDMA toolbox

The first aspect was data processing in the production line. Figure 5.3 shows the levels in this aspect. As can be seen in the figure, there were five levels for each aspect from level zero to level four. The yellow box shows the level of the station before the upgrade and the green box shows the level of the station after the conversion. Data processing is one of the fundamentals of Industry 4.0. Data processing in Industry 4.0 starts with a simple data acquisition and storage until the analysis of data to create an automated process planning and control. For this prototype, level one was achieved. The system was connected to the SCADA software which was able to connect to a database to store and extract data. It also had the ability to record data to a file using various formats or to display the data in the form of a table or graph. The data can then be extracted to generate a report. This was proven in the functionality test, in which data in the database were compared to confirm that it is correctly inserted. The system also has the capability to display and record the trend of certain parameters for analysis and monitoring. For example, in this prototype, the pneumatic pressure and electrical parameters such as the current, voltage and power was constantly monitored and analysed if it is in the permissible limit. This can be seen in the alarm page for example. This system did not manage to achieve a level two because it only monitored and displayed the data and only did a basic analysis of the data. This is because of the scope of the research that did not cover the analysis of data. Although it was not in the scope of this research, the platform for data analysis was already provided. The only thing needed being to develop an algorithm for the analysis function to analyse data that have already been collected and turning these raw data into useful information. As for the ordinary MPS system, it was not connected to any database or monitoring system and therefore only achieved a level zero.

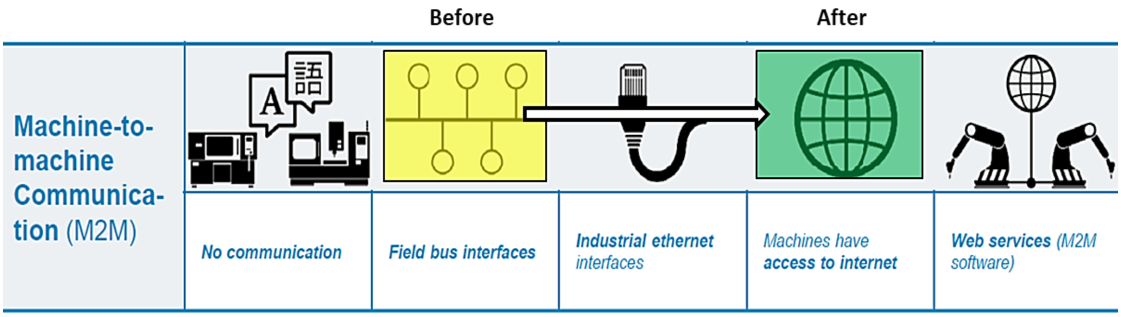

Figure 5.4: Criteria of each level for the second aspect of VDMA toolbox

The second aspect was the machine to machine communication (M2M). Figure 5.4 shows the levels in this aspect. M2M communication is crucial to create an interconnected system. M2M means that the machine can exchange data directly with each other or understand each other without any human interaction. M2M communication usually involves the exchange of data rather than using discrete signals. This system managed to achieve level three for this aspect. This was proven in functionality test, in which data was transferred between devices and through the Internet. The first level was the use of field bus interfaces. A field bus was used to transfer data between machines to reduce the wiring between devices. This system used several bus systems such as the RS485 for the DPM. Another alternative was to use an industrial Ethernet interface which was faster, able to connect to more devices and can transfer a larger size of data. This system used EtherCAT to communicate between PLCs and between the PLCs to the HMIs. The next level was the connectivity to the Internet. All the main components were connected to a gateway which had Internet access. Data from the devices could be directly accessed if configured and hosted correctly. Here, the SCADA software acted as the interface for remote access from the Internet. Data were pooled and exchanged using the web interface built in the software. The level four was not achieved as the web service was not configured. The PLCs had a web service if needed. Therefore, level four is achievable with further development. As for the normal MPS, it only managed to achieve a level one as it used field bus communication for M2M communication between the PLCs. This was done using the RS485 protocol. But this depends strictly on the type on PLC one is using.

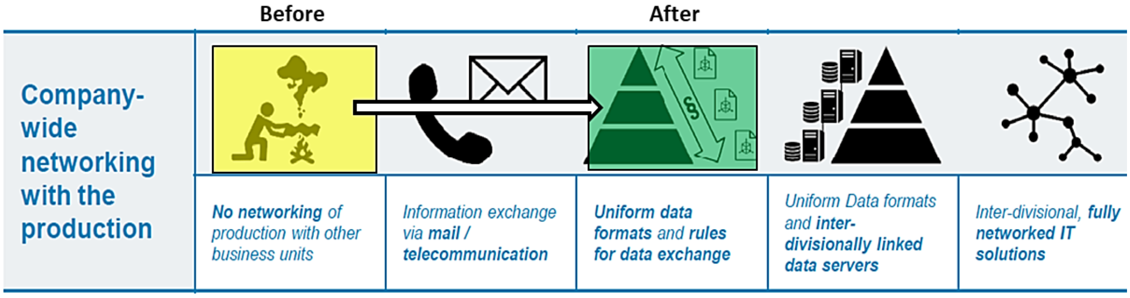

Figure 5.5: Criteria of each level for the third aspect of VDMA toolbox

The third aspect is company-wide networking with production. Figure 5.5 shows the levels in this aspect. In this aspect, the main focus was to interconnect various departments in a company with the production line to open up synergies. As this was only a prototype and the prototype was not really located in a real company, some limitations were applied. This prototype managed to achieve level two. It was connected to the main network and can be accessed within the network. Data can be exchanged using telecommunication, such as an email. Exchange of data between devices is managed by the SCADA software including data exchange using email. This provides a uniform format and rule for the exchange of data. The exchange of data between various devices was tested and confirmed during the functionality test. Next, this system was able to be accessed by various users from various departments using the same interface. The SCADA software acted as the interface between the various systems and to regulate the data exchange. A multi-role user system was developed in which various class of users such as a customer or an engineer, have their own dedicated function. For this aspect, the normal MPS only managed to achieve a level zero as it was not connected to any telecommunication device or was networked in any way.

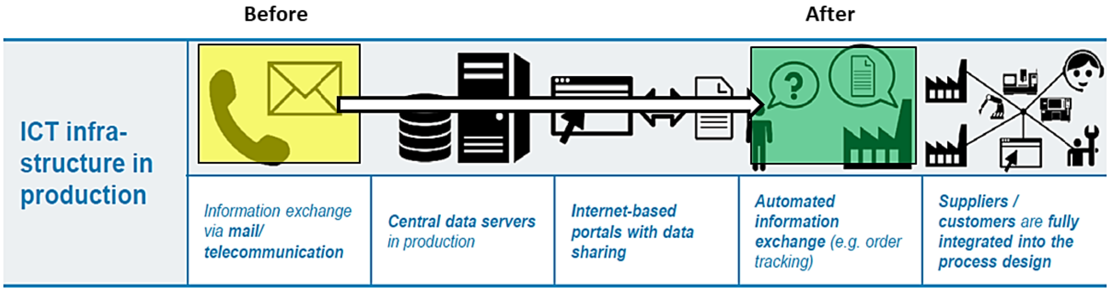

Figure 5.6: Criteria of each level for the fourth aspect of VDMA toolbox

The fourth aspect concerns the infrastructure of information and telecommunication technologies in production. Figure 5.6 shows the levels in this aspect. This aspect focuses on connectivity and the exchange of data. This system managed to achieve level three. This system was connected to a server which hosted a database. In this prototype, data concerning the users and orders, for example, were stored on the connected server. Furthermore, it could be accessed through an Internet-based web application to monitor and control the system. In this system also, a customer can track their order through this web application. The order status of each order is displayed in an order tracking page within the user interface. This was checked each time the workpiece in progress is transferred to the next station. Some data were also exchanged automatically, for example, when the system had finished a process, it will update the status of the production onto the database on the server. In the functionality test, during the production of a product, the status of the production was checked in the check order page. For this aspect, a normal MPS only managed to achieve a level zero as there was no connection to any storage server or to the Internet.

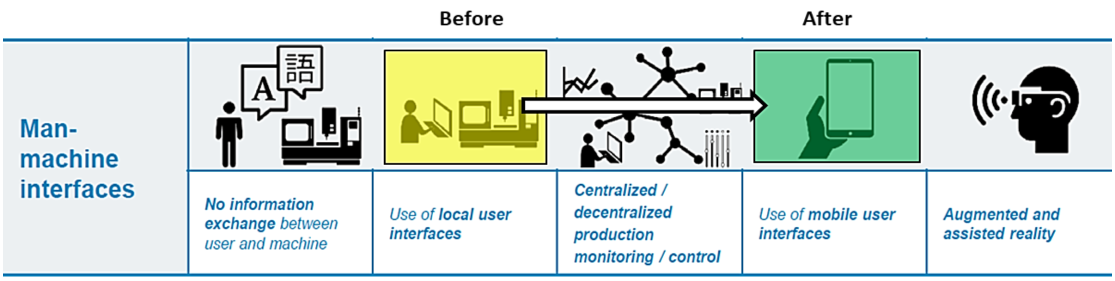

Figure 5.7: Criteria of each level for the fifth aspect of VDMA toolbox

The fifth aspect was the human-machine interface. Figure 5.7 shows the levels in this aspect. The human-machine interface was one of the main developments of this research. In this aspect, a human must be able to communicate with the system using various methods. This was because as production systems are getting more complex, the human-machine interfaces became more important. Humans must be able to interact with the system to give orders or to receive information or the status of production or the health of a machine. This system managed to achieve level three. In this system, the user could interact with the system locally using a touch screen HMI on site. The user could also interact with the system using the SCADA interface from anywhere in the compound of the factory as long as they have a computer that is connected to the same network as the server hosting the SCADA software. The SCADA software also provided a centralized monitoring and control interface to interact with the system. Lastly, the system was able to be accessed using a web browser using mobile devices. This was also provided by the SCADA software. This was checked during the functionality test, in which the user interface on a mobile device was able to exchange data with the system. For the normal MPS, it managed to achieve level one. It had only a local interface that the user could use.

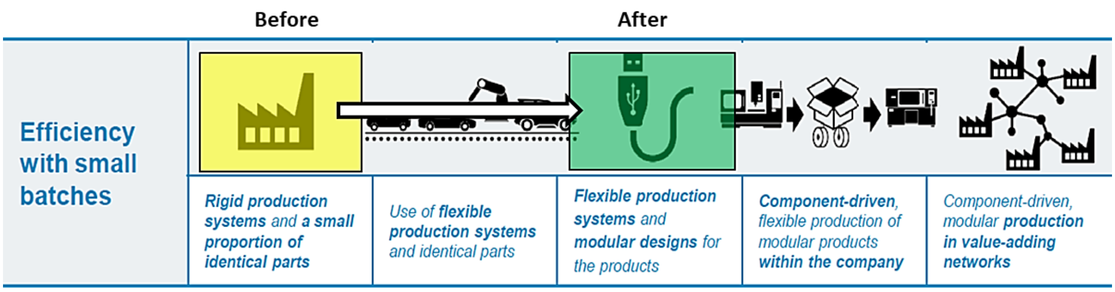

Figure 5.8: Criteria of each level for the sixth aspect of VDMA toolbox

The sixth and last aspect was efficiency in small batches. Figure 5.8 shows the levels in this aspect. The trend nowadays leads to more individual, customizable goods, or goods that are produced in small batches. This will lead to a more complex production process but is needed to stay competitive. The integration of ICT in the production system will help reduce errors in production, increase productivity and efficiency [32]. In this research, the prototype managed to achieve level two. This was because the system itself had limited capabilities. The product used a modular concept in which it still used identical parts but the users could mix and match these identical parts into variants of their own. The products were still manufactured using the same manufacturing process for each variant. During the functionality test, all of the variants were able to be produced. For the normal MPS, it managed to achieve a level zero. It could only produce products in batches. If there was a change in order, the controller needed to be uploaded with the correct program.

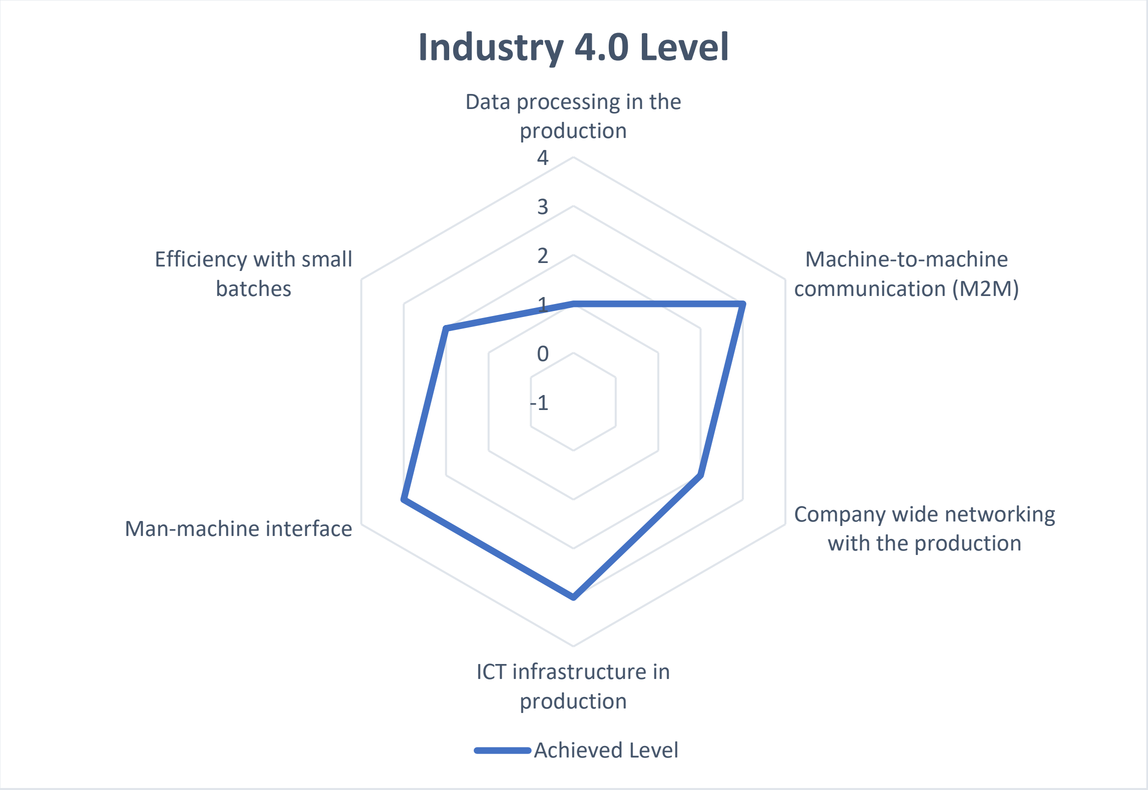

Figure 5.9: Industry 4.0 level radar graph

After all the evaluation was made, the data was plotted using a radar graph as shown in Figure 5.9. The system managed to achieve an average level of 2.3 out of level four. For the normal MPS, it only managed to achieve a level of 0.3.

5.4 Discussion

5.4.1 The Prototype Functionality and Requirement

A prototype has many functions in the real world. It is used either to get feedback from users or to test a certain function. In this case, it was to show the fundamental concept of Industry 4.0 and that it can be developed using standard available parts and be used as a training aid to enhance people’s understanding on the topic. Before this can be done, a system must first of all be working as intended, reliable and consistent. Other than that, the user interface must be user-friendly. The first evaluation was to test its functionality and check whether all of the requirement has been met. From the first evaluation, the system has been found to be working as it should and it could be deduced that it was possible to develop a working prototype to show its concept.

The first evaluation is to check whether all of the components are connected correctly and that signals from these components can be received or transferred correctly and consistently. This is to ensure the reliability of a system. If these signals are transferred and received correctly, the next step of programming, interfacing and digitalizing of the whole system would be easier. Digitalizing means data could be collected thus analysed to extract useable data. As can be seen in the result, various data or signals have managed to be digitalized or collected and displayed correctly. Furthermore, these data are sometimes more accurate than the data that are displayed on the devices' onboard display. This accurate reading is important for certain process that needs precision. There are still some differences in reading between those taken using an additional tool and the reading displayed on the devices. This is maybe because of the reading point in which the external reading was taken using the additional tool. For example, the reading of the voltage is 2 Volt higher than the reading displayed on the device itself. This is not a big problem and can be corrected in the SCADA software. Another aspect of the evaluation is the identification ability of the system using RFID. The RFID tag that was read by the RFID reader has managed to give an accurate reading each time. The RFID reader was not an industrial grade but it managed to perform as intended. The ability to exchange data and the digitalization of signals is the first step towards Industry 4.0.

The ability of the system to operate as intended was also checked thoroughly by checking whether the system could produce all the eight variant it is supposed to produce correctly. This is also to confirm that the system was programmed accordingly. In term of reliability, the system has managed to correctly produce all eight of the variant either individually or in a single order. This also means that data that was inserted in the database is correct and can be read by the system accurately. This shows the integration of ICT that could help manage the different variant correctly without any mistake. There are slight differences in term of time taken to produce each variant especially between the variant with the black cap and the red cap. This is because of the layout of the production line in which the black cap is situated nearer to the capping module. From recorded data, the shortest cycle time recorded was one minute and 6 seconds for variant four and the longest cycle time recorded was one minute and 21 seconds for variant six. The average time to produce one variant was one minute and 13.5 seconds. The total time to produce all of the variants individually was nine minute and 48 seconds. In comparison, the recorded time to produce all of the variants in one order was faster. The time recorded was seven minute and 27 seconds which is about two minutes faster. This is mainly because the system implements a decentralized control system which means each of the stations have its own PLC and does not need to wait for the whole process to complete before starting a new cycle. The cycle time to produce different variants of the product for the upgraded system is supposed to be faster than a normal MPS as no reprogram, setting and uploading of new parameters is needed each time a new variant is to be produced.

The system needs to fulfil several listed requirements. The main requirements were that the system must be able to produce a customized product, digitalization of signals, able to exchange data between various devices, integration of ICT element in the system and the usage of a single interface to manage the exchange of data. From the evaluation and observation made, the system has managed to fulfil all of the requirement that was intended. The ability of the system to exchange data or communicate between the hardware and software shows that the system was integrated correctly. This was to fulfil part of the objective of this research which was to develop, assemble and integrate a smart factory prototype and develop a user interface for the system that could produce customized products. The ability to exchange data between various devices or systems is important in Industry 4.0. It is the key fundamental of Industry 4.0. The ability to exchange data and digitalization means that data could be acquired, processed and used for various functions such as IoT, simulation and data analysis, thus creating a fully autonomous system.

5.4.2 The Prototype Application Level

For the second evaluation, with all the limitations in terms of resources and funding, the system managed to achieve a considerably good level of Industry 4.0. It managed to receive a level of 2.3 compared to a level of 0.3 from a normal MPS. This was an improvement of more than 100% from the normal MPS. Figure 5.10 shows a radar graph for the comparison of a normal MPS with an upgraded MPS. In most aspects, an increase in the Industry 4.0 application level was noticeable. This shows that even a normal system could be upgraded to a certain level of Industry 4.0 and is only limited by one's budget or available parts and also the capability limit of existing hardware and software. From the radar graph displayed, there were a lot of potential or upgrades that could be focused on the system.

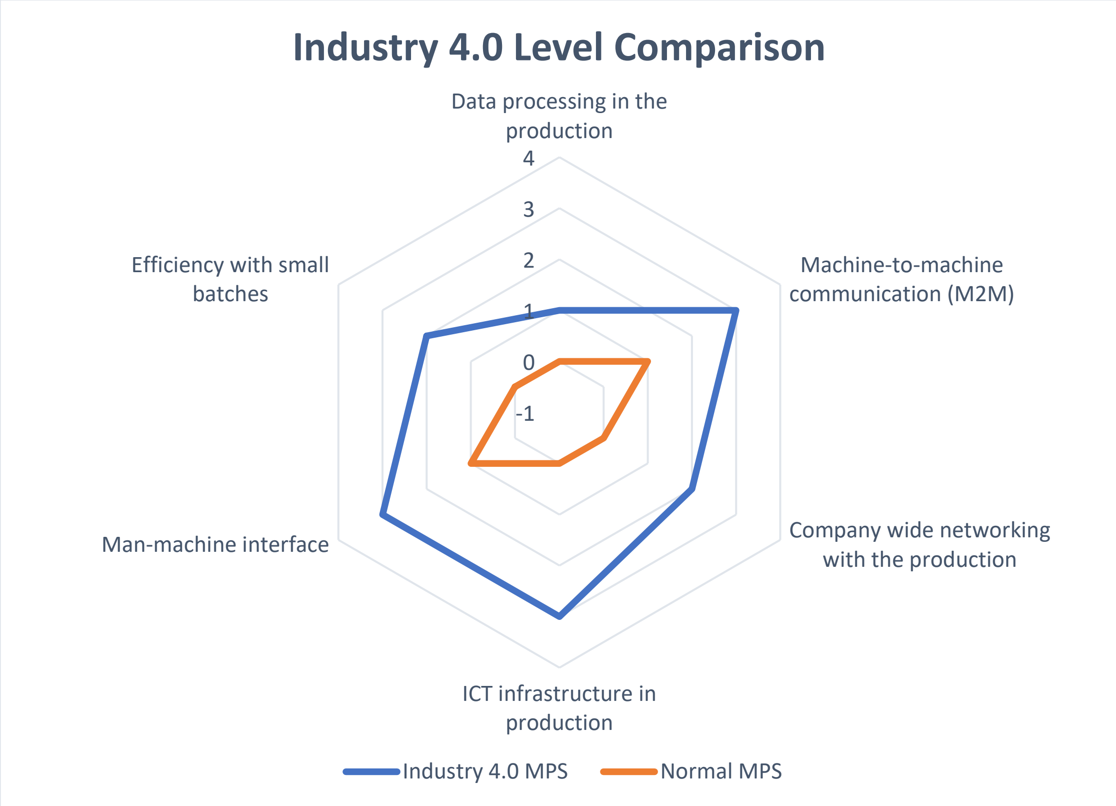

Figure 5.10: Comparison between normal MPS and Industry 4.0 MPS

According to VDMA, there is six important aspects that need to be fulfilled in an Industry 4.0 system. These aspects can be seen in figure 5.10. These aspects are in line with the Industry 4.0 fundamental elements. The main fundamental is the ability to exchange data between various devices and digitalization. This is related to the machine to machine communication, company wide networking with production, ICT infrastructure in production, and man-machine interfaces. The second important fundamental is the integration of ICT in the production line. This is related to data processing in the production, company wide networking with production, and ICT infrastructure in production. Another important fundamental is the customization which is related to the efficiency with small batches. This is among the reason why this toolbox is used as it could prove whether the fundamental concept of Industry 4.0 can be successfully shown or not and at what level.

An evaluation like this will show any weakness that a company is currently facing, and they could choose which of the six aspects they wanted to focus on. For example, this prototype still had a lot of weaknesses in data processing in the production aspect. This is an area for further research and development to fully embrace Industry 4.0. This type of evaluation can also be used by policymakers and the government to see which areas needed improvement and to provide support in terms of the policy, research grants, facilities, experts, funding incentives or tax cuts to companies that are willing to invest in Industry 4.0. For example, certain incentives were given to companies that managed to upgrade their level of Industry 4.0. It can also be used to attract investors in which companies with a certain level of Industry 4.0 readiness are given tax cuts if they invest in this country. Although most of the systems are automated, the opening of new highly automated factories in Malaysia will mean that more highly skilled workers are needed to maintain and operate these types of systems [19], leading to a higher pay [35]. However, to accomplish this, the future workforce must first be educated and have the skills to maintain and operate an Industry 4.0 system. This is where the prototype comes into play and a proven Industry 4.0 system is important to show the real application and concept of Industry 4.0 and not just a self-claimed Industry 4.0 system which can be misleading.

5.4.3 Skill Sets

From the research carried out, additional observations were made. As suggested in [34], the curriculum today needs to change. In developing this system, the skill sets that were needed to develop, operate and maintain such a system are also important. This finding was based on experience and unofficial feedback from people who had interacted with the system. During the dawn of Industry 3.0, the Mechatronics skill set was introduced. Mechatronics skill sets are still needed, but with the addition of ICT, especially for data exchange and integration. Therefore, basic skills and knowledge in the Mechatronics system or automation including sensors, actuators, and control are still very much needed as suggested in [34]. This is to program, monitor and control an automated production line before it is even interconnected. The additional discipline that needs to be added is ICT [22] and M2M communication. This includes the knowledge of advanced manufacturing and digitalization, for example, additive manufacturing and intelligent robotics.

Students must also have good competencies in ICT. This includes knowing various computer programming languages such as Python and Java which are becoming more and more popular. Computer programming is important to create interfaces and web applications that could be accessed through the Internet. Interfaces are needed to gather data and display it for control and monitoring. With all the available data, knowledge in database management is also important to store and manage various data. Students must have the capability to create, connect, manage and extract data from a database. Other than that, students must also have the ability to set up a network to enable them to interface and create a connection to exchange data between systems. ICT subjects are important in Industry 4.0 as there will be a lot of data exchange and communication through the Internet. The use of cloud computing will also increase. Therefore, the knowledge and skills on how to set up a connection and communicate with a cloud service are needed. Cybersecurity is a big issue in Industry 4.0. Therefore, the ability to safeguard data and systems from cyber-attack is important. For example, they must know how to set up a firewall.

Students must also have the ability to integrate various systems with each other. They need to learn various communication protocols to enable them to synchronize each system. Nowadays, there are many ways to connect various systems from different solution providers. It can either be hardware-based or software-based such as by using Open Platform Communication (OPC) to interconnect various systems from various solution providers, which therefore requires the know-how. Analytic skills are also important to analyse data collected from the system. These data need to be analysed and converted into useful data before it can be used to make decisions by the machine. Therefore, knowledge on how to collect data and formulate it into usable data is important. To complete the pillars of Industry 4.0, knowledge of animation or graphic design is also needed if one wants to apply AR in their factory. They must have the skills to link certain graphics to a device so that it could give a response. These are among the skill sets that need to be focused on to produce an Industry 4.0 ready workforce of the future.

5.4.4 Industrial Potential

This study was mainly focused on developing a prototype as a reference and as a training aid to help people understand the concept of Industry 4.0 better. It was not intended to be used in the industry. However, this does not mean that the concept used in this system cannot be applied in the industry. This type of system is suitable for small-medium industries rather than multinational companies. Among the concepts that could be implemented are the remote monitoring and controlling of the system, the use of databases and the customization of the product by introducing variants of the same group of products.

Using SCADA as the system's backbone to integrate the whole system is fast and efficient especially to enable data exchange between various devices with different protocols and creating an interface to display data. The main problem is that the current system must be at least equipped with Industry 3.0 technologies or the cost will be too expensive to upgrade a manual conventional system into an automated system and thus into an Industry 4.0 compliant system. Also, the return of an investment will take too long. Another problem that needs to be addressed if this system is to be implemented in the industry is the ordering system. The ordering system was developed also using the SCADA software and this system is only capable of handling a limited number of users at the same time depending on the SCADA license that is purchased and the ordering system is not equipped with an online payment system. Catering a huge number of online users is possible but will involve huge investment but then this is easily overcome using various online ordering and payment system. Other than that, Cybersecurity of the system must also be looked into and enhanced.

5.4.5 Cost

In terms of cost, which is a big issue for companies to adopt Industry 4.0 technologies and for training institutes to start offering courses on this topic, a comparison between buying a new system and upgrading an existing one was made. From this research, it was deducted based on the observation made that converting a non-Industry 4.0 system into an Industry 4.0 system is cheaper but also depends on the state of the existing system. The cost of buying a new Industry 4.0 MPS from

Festo is about RM380,000. On the other hand, conversion cost about RM50,000 mainly for the PLC and SCADA software. This was provided that the stations were already available. This was a lot of savings considering the tight budget that the training institute had. Furthermore, these stations are used in the WorldSkills competition participated by many TVET training institutes. Therefore most TVET training institutes already have similar stations that are yet to be upgraded. These training institutes can consider upgrading their current stations with Industry 4.0 element to save cost and time using the same methodology and model as described in this work.

As stated before, this depends on the state of an existing system. An Industry 3.0 system is cheaper to upgrade but may be more complex to integrate than upgrading an Industry 2.0 system which will cost more but is easier to integrate as a more common and unified system which can be selected from the beginning. Thus, to save cost, it is better to upgrade an existing system and at the same time learn how to integrate the system.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

This chapter discusses the conclusion of this research based on the discussion and analysis made in the previous chapter. Then, recommendations for future research are suggested.

6.1 Conclusion

Industry 4.0 is the way forward into the future of industrialization. Various factors such as advancement in ICT, the innovation of new technology, an efficient supply chain, affordable cost of automation, and the change in customer buying habits make this revolution seemingly unstoppable. This revolution is still emerging, therefore, understanding the fundamentals of Industry 4.0 is crucial. One of the solutions is to develop a prototype to show the concept and solutions for Industry 4.0. This was done using currently available parts and components to reduce cost and to show that it is possible to upgrade an Industry 3.0 system into an Industry 4.0 system, as Industry 4.0 devices are expensive. The main goal was to create a prototype to showcase the concept of Industry 4.0 to equip the future workforce with the right skill sets and knowledge for Industry 4.0. This research is applied research to systematically develop a smart factory prototype in the context of Industry 4.0.

This research had three main objectives. The first objective was to derive a domain-spanning principle solution for a smart factory prototype in the context of Industry 4.0 and utilize a specification technique called the Conceptual Design Specification Technique for the Engineering of Complex Systems (CONSENS) to specify a system model. This is an approach to clarify the interactions of various devices or domain in a system. This objective was achieved in which three domain specific components were derived which are the mechanical domain, electrical and electronic domain and information and communication technology domain. The system model is shown using the CONSENS active structure model for the overall prototype and for each station was derived. These models, which can be seen in Chapter Four, show the overall interaction between various elements in a system in terms of information flow, energy flow and material flow. This model was the basis of developing the smart factory prototype.

The second objective was to develop, assemble, integrate and interface a smart factory prototype in the context of Industry 4.0 including developing its user interface by retrofitting an existing system. In this research, a working prototype of a smart factory was developed and assembled using currently available components. A user interface was also developed and interfaced with the prototype. This was achieved by using the SCADA software as the backbone that linked various devices and provided access from the Internet. The interface managed to display various data and allowed users to interact or give certain commands to the system. The system was then proven to function as intended by undergoing various functionality tests. The user interface was also tested during the functionality test. This proves that building a smart factory prototype using currently available components is possible. The feedback from people seeing the system as shown in Appendix G was also very positive. Therefore, the second objective was achieved.

The last objective was to evaluate the smart factory prototype in terms of functionality and application level of Industry 4.0. This was mainly to support the previous objectives. This objective was also achieved in which two main evaluations were carried out and a few observation was made. The first evaluation was a functionality test and the second was an evaluation using the VDMA Industry 4.0 toolbox. The functionality test showed that the prototype was working correctly as intended. The system was able to exchange data between various systems and the digitalization of signals was checked. It was also possible to interact with the system through the Internet. This proved that it was possible to upgrade an existing system with Industry 4.0 elements. The second evaluation showed that the system managed to achieve a considerable level of Industry 4.0 and there was an improvement over the normal system. The existing system only managed to obtain a level of 0.3 whereas the upgraded system managed to achieve a level of 2.3. An additional observation was also made on the skill sets needed for Industry 4.0 and the cost of buying a whole complete system in contras on upgrading an existing one.

As a conclusion, this research had managed to produce a functional Industry 4.0 prototype that could be used to show the fundamentals of Industry 4.0 by upgrading an existing system and using currently available components. With this, people can use this prototype to understand Industry 4.0 better and carry out evaluations to see whether Industry 4.0 is suitable for their organization. The system was showcased to various parties as can be seen in Appendix G. It is intended to train future workforces to prepare for the coming industrial revolution. Other than that, academicians can learn and evaluate this system to develop suitable curriculums and investigate the skill sets needed to embrace Industry 4.0. This development could lead the way in developing a full Industrial 4.0 system in the future and help people understand the concept of Industry 4.0.

6.2 Recommendations

This research is crucial for various stakeholders, especially training institutes, to be utilised as a demonstrator, training aid or an evaluation system to learn, teach and help people understand Industry 4.0 better. As discussed, the best way is to upgrade or equip an existing system with Industry 4.0 elements. This depends on the existing system, whereby it is cheaper and gives the opportunity for the developer to learn how to integrate such a system. A budget to buy a new system is hard to come by. Therefore, while waiting for funding to be available, the option is conversion and to learn from it at the same time.

Another recommendation is to add Industry 4.0 elements as a competency in the National Occupational Skill Standard (NOSS) for students, especially TVET students, for example, those who are pursuing their *Diploma Kemahiran Malaysia*. This is because as shown in the evaluation, with formal training, the knowledge of students on this topic is very limited. The competencies and fields related to Industry 4.0 need to be determined. The focus should be on the fields that are directly related such as industrial automation, but not limited to only these fields as everyone should have basic knowledge on this topic. A prototype could help academicians or TVET instructors to identify which competencies are relevant and important to which field of study. Then, these competencies can be adopted in the current syllabus to teach students or the public generally.

Another recommendation especially pertaining to this research is to use a bigger sample size for the evaluation. This is to get more data to evaluate and get more feedback on the system. Therefore, the system must be displayed to the public or used intensively to teach people about Industry 4.0. Other than that, it is also suggested to get experts' evaluation on the system for a more thorough and convincing analysis.

6.3 Scalability of Research Outcomes

First of all, the system can be integrated with other Industry 4.0 technology pillars that have not been covered in this prototype. An example is to develop a cybersecurity system for the system to safeguard it from cyber-attacks. Next is to integrate additive manufacturing technology to create a more customizable product variant. Other than that is to use data science or integrate an analysis system that will analyse data collected from the system mainly for maintenance and quality enhancement. An algorithm for AI can be embedded to make the system more autonomous and to provide recommendations on certain things based on the analysed data. AR or VR can also be integrated for a more intuitive system and better user experience, for example, to provide an intuitive guided graphical SOP. Another technology that can be integrated is to create a digital copy of the system for the visualisation and simulation of the whole production system. This could be done using an automation simulation software such as Automation Studio. Cloud computing and services are also an important component of Industry 4.0 to provide remote access and other services such as data analysis, machine learning and remote data display. Lastly, another important element that could be added is an intelligent robot such as a Cobot that could work side-by-side with a human.

Another further development is to integrate advanced sensory systems that could connect directly to a controller or a cloud system. These sensors should also have the capability of a self-diagnostic system that could detect any fault. This is because sensors are important for data acquisition used for analysis.

A further scalability possibility is using the Uber concept. The concept is by connecting various production systems or a machine to the Internet, and anyone could accept a job request posted by anyone to manufacture a part of a product or even a complete product. The idea is that a job request is posted online, and anyone could accept this job request according to their capability. This is, among others, so that a product can be produced locally to reduce logistics costs. If the job request is accepted, the requestor will directly send encrypted data of the part that needs to be manufactured directly to its production line or machine. After the product is produced, it will then be sent to a location as instructed by the requestor. In this way, manufacturers could cooperate with each other, reducing the loss of the idle machine.

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APPENDIX A

IO ALLOCATION CHECKLIST FOR STATION 1

INPUT					OUTPUT				
Label	**Address**	**Type**	**Description**	**√ / X**	**Label**	**Address**	**Type**	**Description**	**√ / X**
X0	%IX0.0	BOOL	Arm at RFID Pos		Y0	%QX0.0	BOOL	Stack 1 arm push WP	
X1	%IX0.1	BOOL	Arm at Stack 1		Y1	%QX0.1	BOOL	Stack 2 arm push WP	
X2	%IX0.2	BOOL	Arm at Stack 2		Y2	%QX0.2	BOOL	Arm Move left	
X3	%IX0.3	BOOL	Arm at next Station		Y3	%QX0.3	BOOL	Arm move right	
X4	%IX0.4	BOOL	Arm Up		Y4	%QX0.4	BOOL	Arm Down	
X5	%IX0.5	BOOL	Arm down		Y5	%QX0.5	BOOL	Gripper close	
X6	%IX0.6	BOOL	Optical Sensor at gripper		Y6	%QX0.6	BOOL	Not in use	
X7	%IX0.7	BOOL	Not in use		Y7	%QX0.7	BOOL	Not in use	
X8	%IX0.8	BOOL	Start		Y8	%QX0.8	BOOL	Start Lamp	
X9	%IX0.9	BOOL	Reset		Y9	%QX0.9	BOOL	Reset Lamp	
X10	%IX0.10	BOOL	Not in use		Y10	%QX0.10	BOOL	Not in use	
X11	%IX0.11	BOOL	Not in use		Y11	%QX0.11	BOOL	Not in use	
X12	%IX0.12	BOOL	Stack 1 arm extend		Y12	%QX0.12	BOOL	Not in use	
X13	%IX0.13	BOOL	Stack 2 arm extend		Y13	%QX0.13	BOOL	Signal lamp green	
X14	%IX0.14	BOOL	Stack 1 WP available		Y14	%QX0.14	BOOL	Signal lamp yellow	
X15	%IX0.15	BOOL	Stack 2 WP available		Y15	%QX0.15	BOOL	Signal lamp red	

APPENDIX B

IO ALLOCATION CHECKLIST FOR STATION 2

INPUT					OUTPUT				
Label	Address	Type	Description	√ / X	Label	Address	Type	Description	√ / X
X0	%IX0.0	BOOL	Cap Dispenser 1 cylinder extend		Y0	%QX0.0	BOOL	Cap dispenser 1 arm push WP	
X1	%IX0.1	BOOL	Cap Dispenser 2 cylinder extend		Y1	%QX0.1	BOOL	Cap dispenser 2 arm push WP	
X2	%IX0.2	BOOL	Not in use		Y2	%QX0.2	BOOL	Retract stopper at filling Pos	
X3	%IX0.3	BOOL	Workpiece at filling Pos		Y3	%QX0.3	BOOL	Not in use	
X4	%IX0.4	BOOL	Workpiece available at start		Y4	%QX0.4	BOOL	Conveyor on	
X5	%IX0.5	BOOL	Workpiece at Capping Pos		Y5	%QX0.5	BOOL	Retract stopper at capping Pos	
X6	%IX0.6	BOOL	Cap dispenser 2 Empty		Y6	%QX0.6	BOOL	Linear drive move Back	
X7	%IX0.7	BOOL	Cap dispenser 1 Empty		Y7	%QX0.7	BOOL	Linear drive move Front	
X8	%IX0.8	BOOL	Start		Y8	%QX0.8	BOOL	Start lamp	
X9	%IX0.9	BOOL	Reset		Y9	%QX0.9	BOOL	Reset lamp	
X10	%IX0.10	BOOL	Not in use		Y10	%QX0.10	BOOL	Not in use	
X11	%IX0.11	BOOL	Linear drive at conveyor		Y11	%QX0.11	BOOL	Vacuum on	
X12	%IX0.12	BOOL	Cap gripped		Y12	%QX0.12	BOOL	Electrical drive moves up	
X13	%IX0.13	BOOL	Linear drive at cap dispenser 2		Y13	%QX0.13	BOOL	Electrical drive moves down	
X14	%IX0.14	BOOL	Linear drive at cap dispenser 1		Y14	%QX0.14	BOOL	Activate Infill 1	
X15	%IX0.15	BOOL	Not in use		Y15	%QX0.15	BOOL	Activate Infill 2	

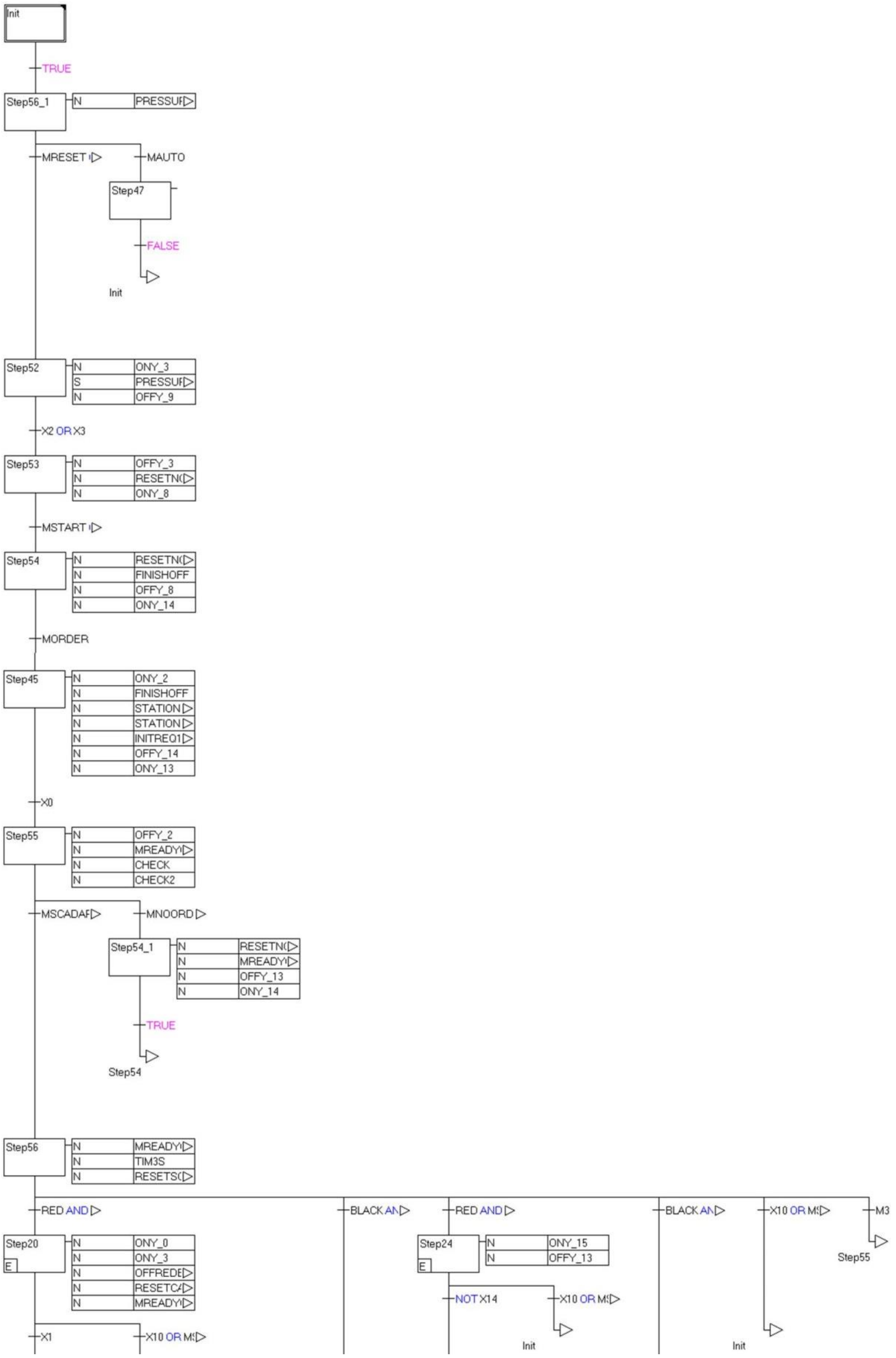
APPENDIX C

IO ALLOCATION CHECKLIST FOR STATION 3

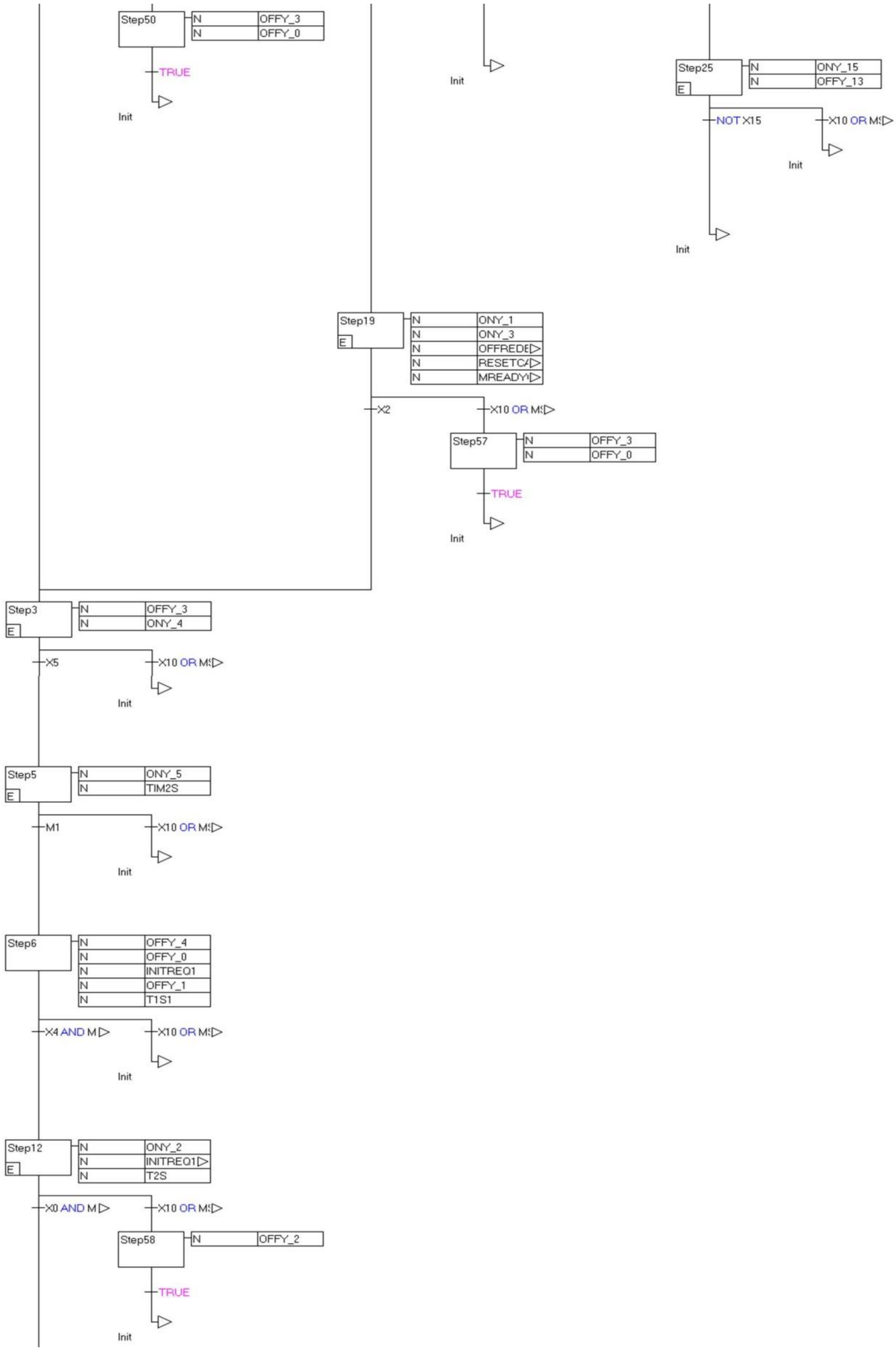
INPUT					OUTPUT				
Label	**Address**	**Type**	**Description**	√ / X	**Label**	**Address**	**Type**	**Description**	√ / X
X0	%IX0.0	BOOL	GATE 1 EXTENDED		Y0	%QX0.0	BOOL	Not in use	
X1	%IX0.1	BOOL	GATE 1 RETRACTTED		Y1	%QX0.1	BOOL	EXTEND GATE 1	
X2	%IX0.2	BOOL	GATE 2 EXTENDED		Y2	%QX0.2	BOOL	EXTEND GATE 2	
X3	%IX0.3	BOOL	GATE 2 RETRACTED		Y3	%QX0.3	BOOL	CONVEYOR ON	
X4	%IX0.4	BOOL	WP ENTER SLIDE		Y4	%QX0.4	BOOL	RETRACT STOPPER	
X5	%IX0.5	BOOL	INDUCTIVE SENSOR		Y5	%QX0.5	BOOL	Not in use	
X6	%IX0.6	BOOL	OPTICAL SENSOR		Y6	%QX0.6	BOOL	Not in use	
X7	%IX0.7	BOOL	WP AVAILABLE AT START		Y7	%QX0.7	BOOL	Not in use	
X8	%IX0.8	BOOL	START		Y8	%QX0.8	BOOL	START LAMP	
X9	%IX0.9	BOOL	RESET		Y9	%QX0.9	BOOL	RESET LAMP	
X10	%IX0.10	BOOL	STOP		Y10	%QX0.10	BOOL	Not in use	
X11	%IX0.11	BOOL	Not in use		Y11	%QX0.11	BOOL	Not in use	
X12	%IX0.12	BOOL	Not in use		Y12	%QX0.12	BOOL	Not in use	
X13	%IX0.13	BOOL	Not in use		Y13	%QX0.13	BOOL	Not in use	
X14	%IX0.14	BOOL	Not in use		Y14	%QX0.14	BOOL	Not in use	
X15	%IX0.15	BOOL	Not in use		Y15	%QX0.15	BOOL	Not in use	

APPENDIX D

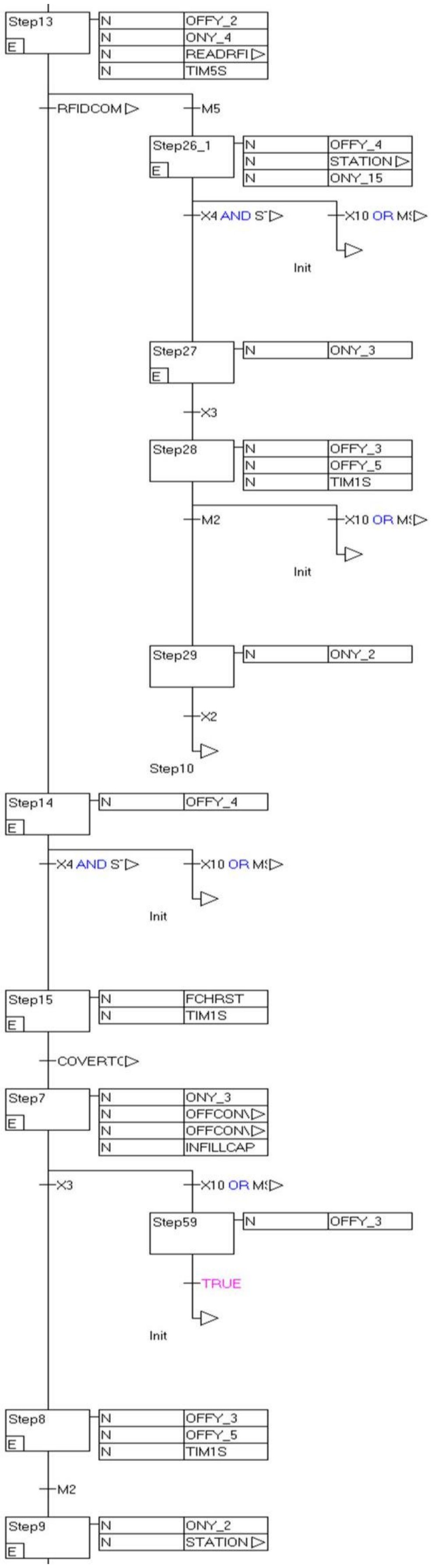
PLC Program for station 1



APPENDIX D

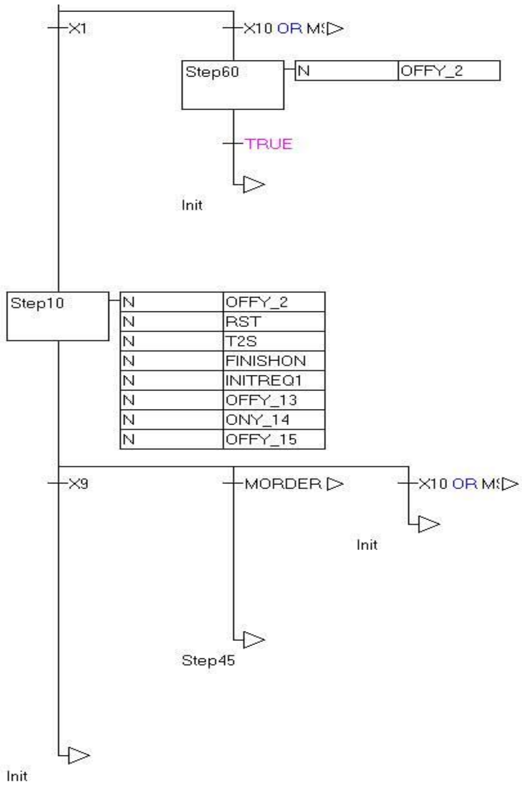

Step50
N OFFY_3
N OFFY_0
TRUE
Init
Init
Step25
N ONY_15
N OFFY_13
NOT X15
X10 OR M
Init
Init
Step19
N ONY_1
N ONY_3
N OFFREDE
N RESETC
N MREADY
X2
X10 OR M
Step57
N OFFY_3
N OFFY_0
TRUE
Init
Step3
N OFFY_3
N ONY_4
X5
X10 OR M
Init
Step5
N ONY_5
N TIM2S
M1
X10 OR M
Init
Step6
N OFFY_4
N OFFY_0
N INITREQ1
N OFFY_1
N T1S1
X4 AND M
X10 OR M
Init
Step12
N ONY_2
N INITREQ1
N T2S
X0 AND M
X10 OR M
Step58
N OFFY_2
TRUE
Init

APPENDIX D



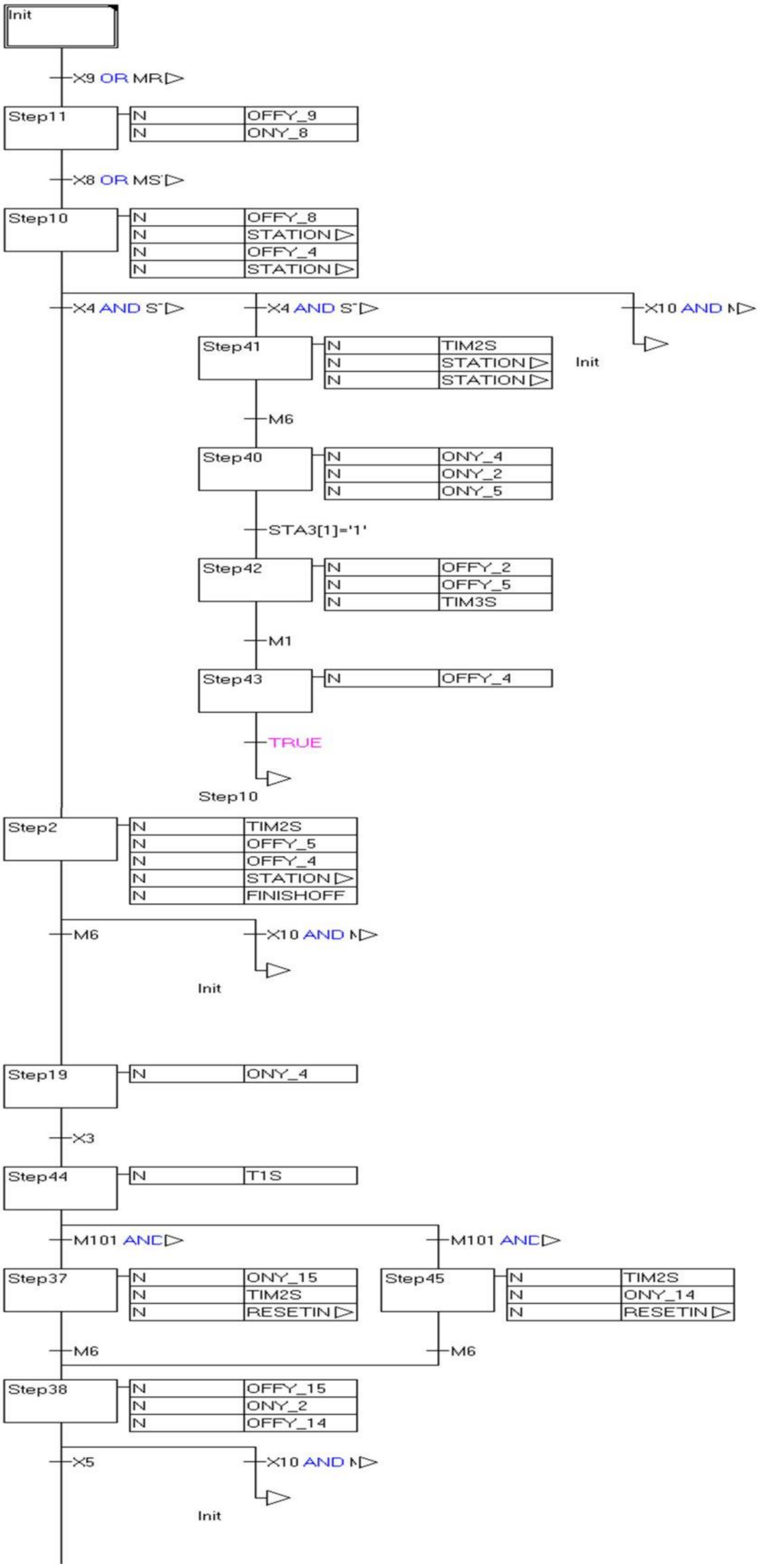
Step13
E
N OFFY_2
N ONY_4
N READRFI
N TIM5S
RFIDCOM
M5
Step26_1
E
N OFFY_4
N STATION
N ONY_15
X4 AND S
X10 OR M
Init
Step27
E
N ONY_3
X3
Step28
N OFFY_3
N OFFY_5
N TIM1S
M2
X10 OR M
Init
Step29
N ONY_2
X2
Step10
Step14
E
N OFFY_4
X4 AND S
X10 OR M
Init
Step15
E
N FCHRST
N TIM1S
COVERTC
Step7
E
N ONY_3
N OFFCON
N OFFCON
N INFILLCAP
X3
X10 OR M
Step59
N OFFY_3
TRUE
Init
Step8
E
N OFFY_3
N OFFY_5
N TIM1S
M2
Step9
E
N ONY_2
N STATION

APPENDIX D

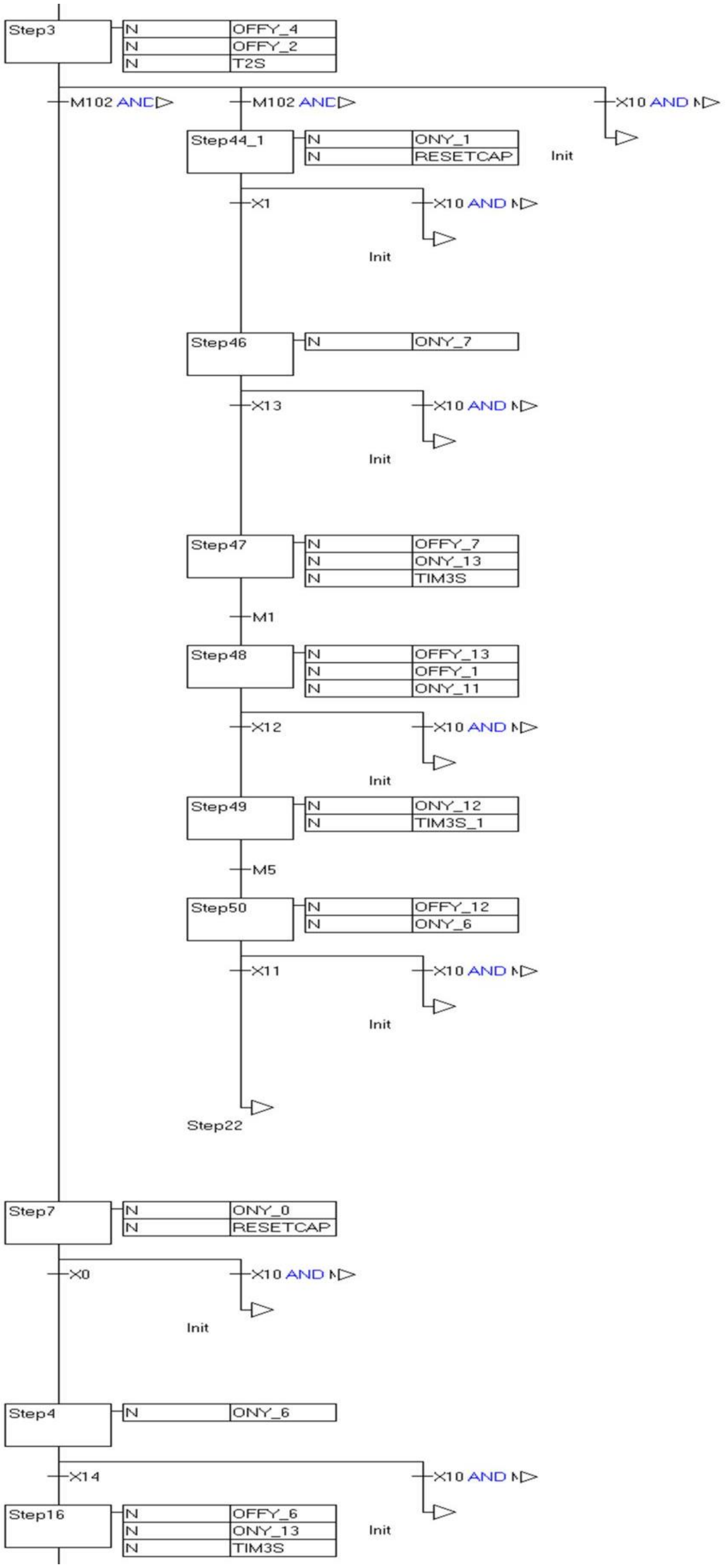

X1
X10 OR M
Step60
N
OFFY_2
TRUE
Init
Step10
N
OFFY_2
N
RST
N
T2S
N
FINISHON
N
INITREQ1
N
OFFY_13
N
ONY_14
N
OFFY_15
X9
MORDER
X10 OR M
Init
Step45
Init

APPENDIX E

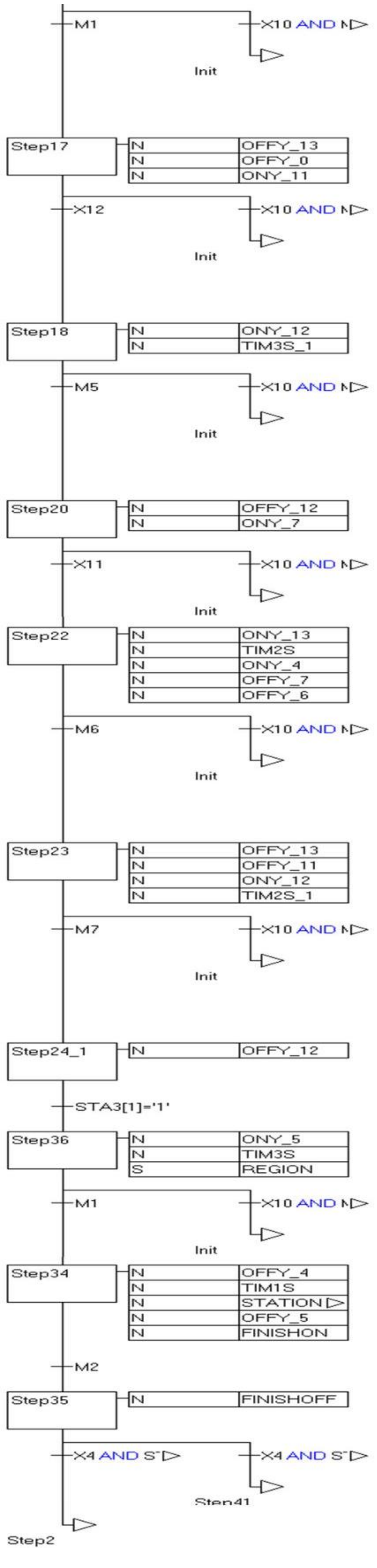
PLC Program for station 2



APPENDIX E

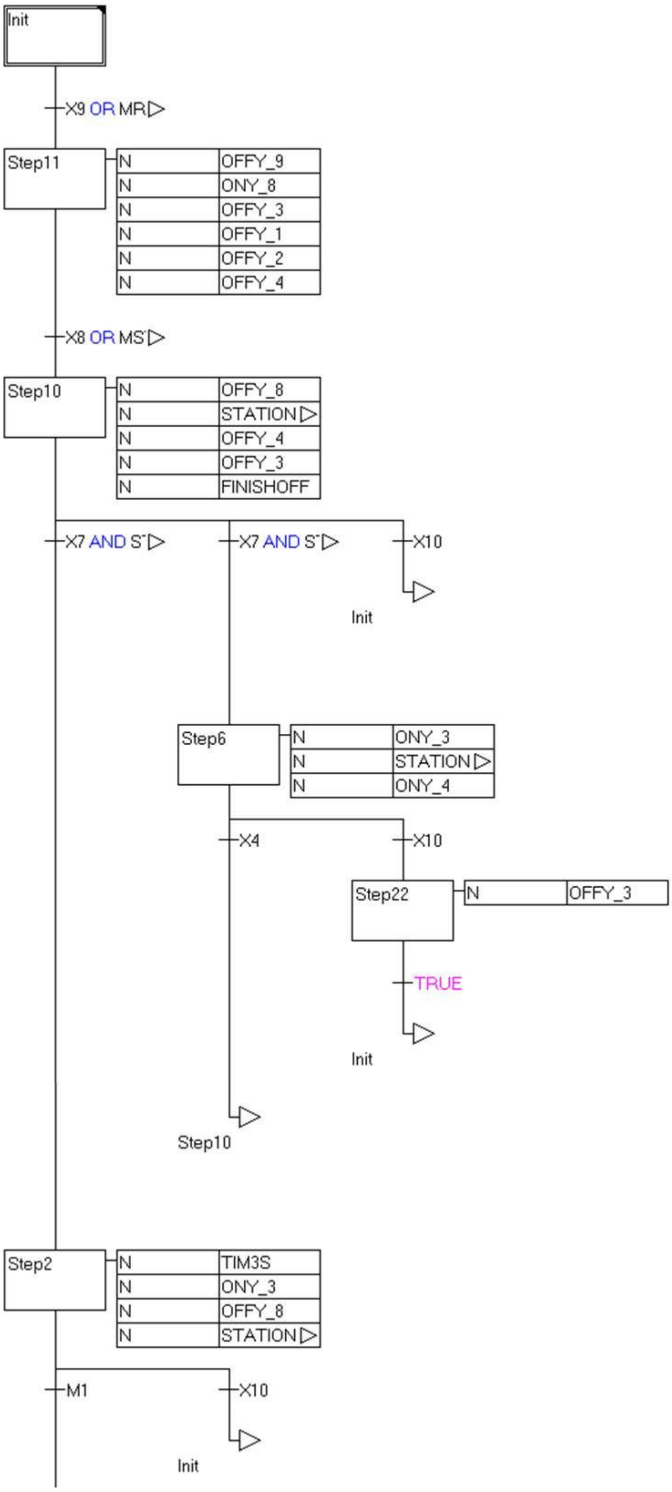

Step3
N OFFY_4
N OFFY_2
N T2S
M102 ANC
M102 ANC
X10 AND N
Step44_1
N ONY_1
N RESETCAP
Init
X1
X10 AND N
Init
Step46
N ONY_7
X13
X10 AND N
Init
Step47
N OFFY_7
N ONY_13
N TIM3S
M1
Step48
N OFFY_13
N OFFY_1
N ONY_11
X12
X10 AND N
Init
Step49
N ONY_12
N TIM3S_1
M5
Step50
N OFFY_12
N ONY_6
X11
X10 AND N
Init
Step22
Step7
N ONY_0
N RESETCAP
X0
X10 AND N
Init
Step4
N ONY_6
X14
X10 AND N
Step16
N OFFY_6
N ONY_13
N TIM3S
Init

APPENDIX E

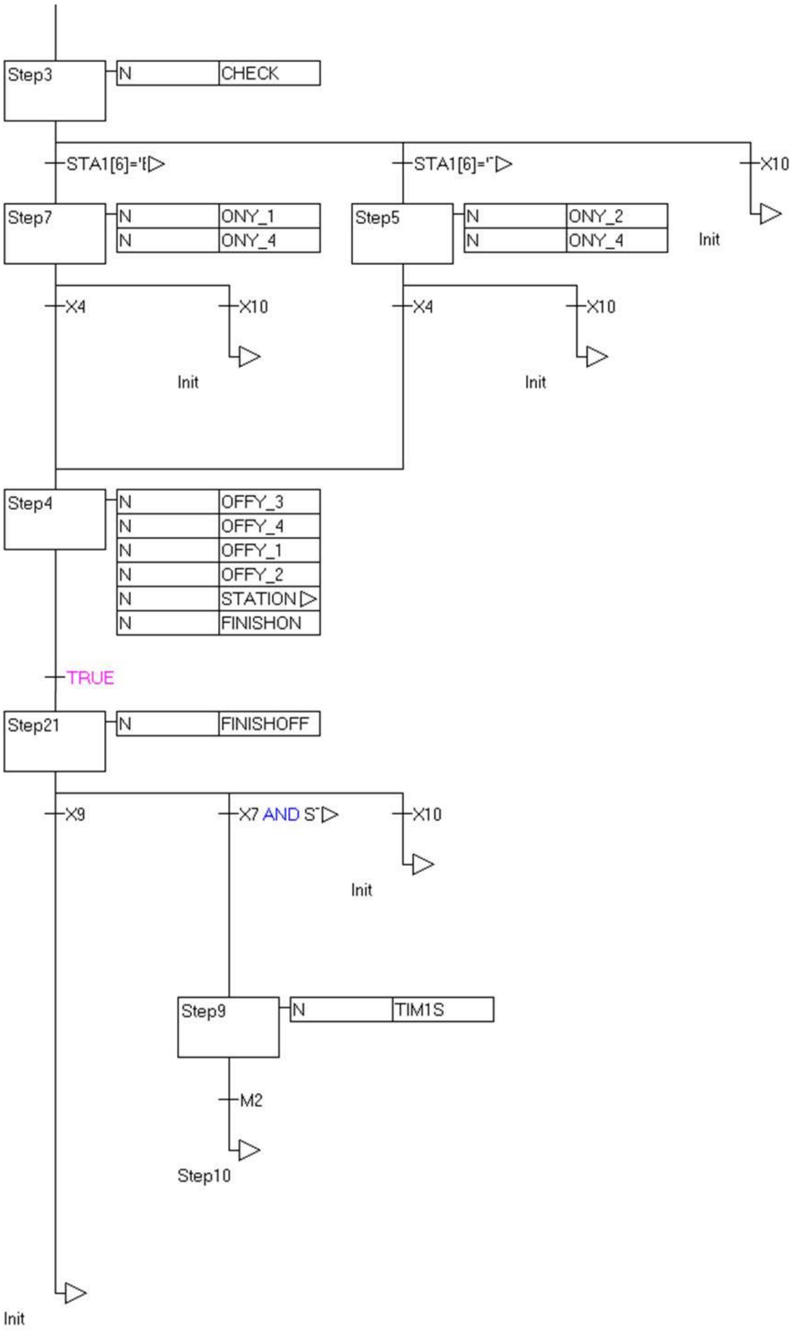

M1
X10 AND N
Init
Step17
N OFFY_13
N OFFY_0
N ONY_11
X12
X10 AND N
Init
Step18
N ONY_12
N TIM3S_1
M5
X10 AND N
Init
Step20
N OFFY_12
N ONY_7
X11
X10 AND N
Init
Step22
N ONY_13
N TIM2S
N ONY_4
N OFFY_7
N OFFY_6
M6
X10 AND N
Init
Step23
N OFFY_13
N OFFY_11
N ONY_12
N TIM2S_1
M7
X10 AND N
Init
Step24_1
N OFFY_12
STA3[1]='1'
Step36
N ONY_5
N TIM3S
S REGION
M1
X10 AND N
Init
Step34
N OFFY_4
N TIM1S
N STATION
N OFFY_5
N FINISHON
M2
Step35
N FINISHOFF
X4 AND S
X4 AND S
Step41
Step2

APPENDIX F

PLC Program for station 3



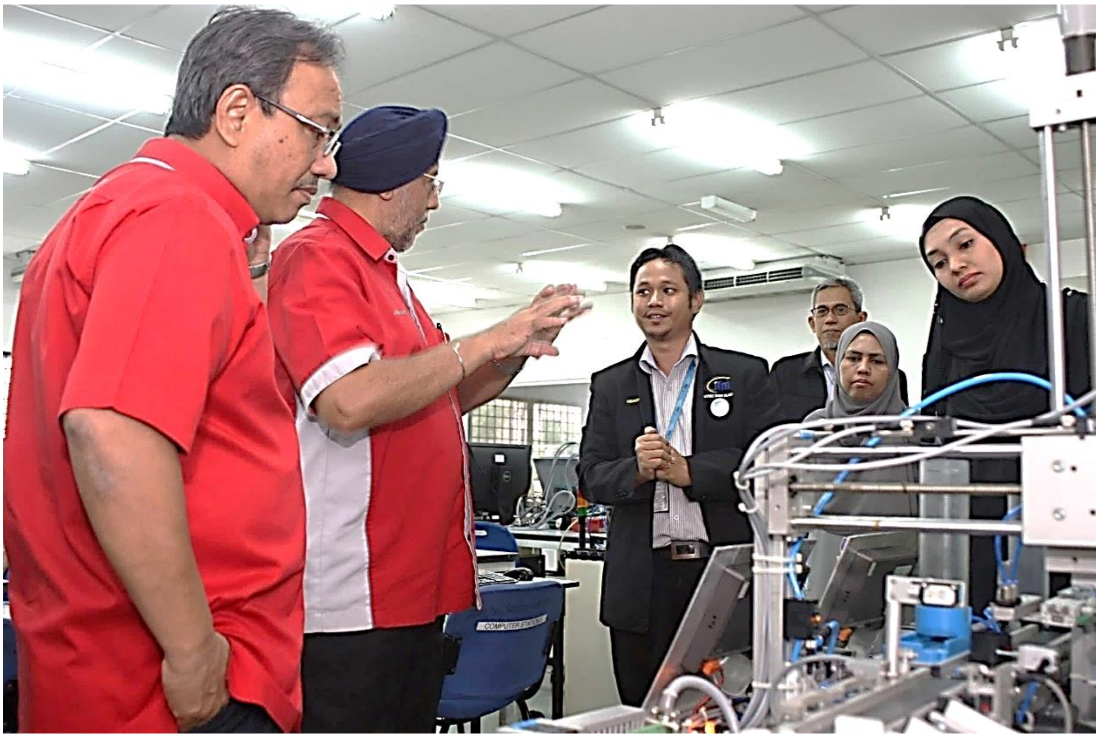
APPENDIX F


Step3
N
CHECK
STA1[6]='t
STA1[6]='
X10
Init
Step7
N
ONY_1
N
ONY_4
Step5
N
ONY_2
N
ONY_4
X4
X10
Init
X4
X10
Init
Step4
N
OFFY_3
N
OFFY_4
N
OFFY_1
N
OFFY_2
N
STATION
N
FINISHON
TRUE
Step21
N
FINISHOFF
X9
X7 AND S
X10
Init
Step9
N
TIM1S
M2
Step10
Init

APPENDIX G

Demonstrations of the Prototype Photos

Demonstration of the prototype to delegates from Kilang Wang Bank Negara



Demonstration of the prototype to delegates from MIDA

APPENDIX G

Demonstration of the prototype to the Chief Director of Jabatan Tenaga Manusia, KSM

Demonstration of the prototype to delegates from Perbadanan Kemajuan Negeri Perak (PKNP) / Ernst & Young Advisory Services

APPENDIX G

Demonstration of the prototype to delegates from Mitsubishi Motors Malaysia Sdn. Bhd.

Demonstration of the prototype to delegates from Indonesia

APPENDIX G

Demonstration of the prototype to the Minister of Human Resources, KSM

Demonstration of the prototype to delegates from the Ministry of Health, Labour and Welfare Japan

APPENDIX G

Demonstration of the prototype to delegates from Jabatan Pembangunan Sumber Manusia Negeri Sabah

Demonstration of the prototype conjunction with the visit of the Minister of Human Resources broadcasted in TV2 news

APPENDIX G

Demonstration of the prototype for the DIALOG show with the Minister of Human Resources broadcasted in TV1

Demonstration of the prototype to delegates from Daikin Malaysia Sdn. Bhd.

APPENDIX G

Demonstration of the prototype to delegates from Unit Perancang Ekonomi, Jabatan Perdana Menteri

Demonstration of the prototype to delegates from Saudi Arabia with the Deputy Minister Of Human Resources

VITA

The author was born in 1983, in Kuala Lumpur, Malaysia. He then went to the UK until the age of 5 following his family. He went to Sekolah Menengah Agama Persekutuan, Labu, Negeri Sembilan, Malaysia for his secondary school. After passing his SPM, he was offered a scholarship to study in Germany. He did his A-Level and studied the German language in INTEC, UiTM, Shah Alam. After that, he pursued his professional degree at the Aachen University of Applied Science (Fachhochschule), Aachen, Germany which is one of the elite Fachhochschule in Germany. He graduated with a Diplom Ingenieur (FH) in Mechatronics in 2009. During his study, he undergoes several hands-on practical training in HICOM Teck See Manufacturing, Malaysia, Eurocopter, Malaysia and Elektrisola, Germany. He did his final year project at APS European Center for Mechatronics. Upon graduation, he worked as an engineer at Perodua Engine Manufacturing, Malaysia. Then, he worked as a vocational Training Officer at ADTEC Shah Alam, in the department of Mechatronics / Automation. He taught subjects such as PLC, Automation Principle, Maintenance, and Installation. During these years, he has been actively involved in various activity and competition. He has brought ADTEC Shah Alam Robotic team to win various competitions. He is also involved in innovation projects and won various innovation competitions. In 2013, he entered the national skill competition instructor for Mechatronics and won the Gold medal with full marks. He is also the coach for the skill competition for the mechatronics field. In 2016, his students represent Malaysia in the ASEAN Skill Competition won the gold medal for Malaysia for the first time and also represented Malaysia in the World Skill Competition in Abu Dhabi. He also has a Diploma Kemahiran Malaysia in Industrial Automation. He received the Service Excellent Award for 2013 and 2016. In 2017, he was awarded as a Professional Technologist by MBOT carrying the title of Ts. In 2019, he received the Excellent Teaching Awards in conjunction with the 24th ILJTM Convocation Ceremony.